A STRATIGRAPHICAL, SEDIMENTOLOGICAL AND PALAEOENVIRONMENTAL ANALYSIS OF HOLOCENE AND PRESENT-DAY COASTAL SEDIMENTATION: WIGTOWN BAY, S.W. SCOTLAND.

BY

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Summary

Evidence of Holocene marine transgression and regression in South-West Scotland is exhibited in the stratigraphical record of present and former coastal deposits. Remnant areas of Holocene coastal (including marine) sediments are preserved at the head of marine inlets and estuaries along the northern shore of the Solway Firth and may extend up to 10km inland, indicating significant changes in coastal configuration as a result of marine transgression and regression during the last 10,000 years.

At the head of Wigtown Bay, former Holocene coastal deposits are well exposed along the incised meanders of the upper Cree estuary and Palnure Burn. Referred to in the literature as "carse deposits", these sediments are products of several different environments.

During late-Pleistocene times and very early in the Holocene Epoch, the upper Cree estuary area north of Creetown was a low lying boggy environment. The area was marginally marine in character. The exact position of the palaeo-Cree is uncertain but the river flowed in a general NW to SE direction and may have been braided. The marine waters of the Holocene marine transgression flooded northwards, penetrating the upper Cree estuary c. 7,900 years B.P., leading to the deposition of low to high tidal-flats. By 6,480±107 years B.P. local regression had begun and seaward progradation of high upper tidal-flats and marsh had started. This environmental situation prevailed until 5,000 years B.P., when incision occurred and terrestrial conditions became dominant.

In the lower Cree estuary, waters of the Holocene marine transgression initially flooded the lower courses of rivers and rose to flood the hollows in the uneven surface of the fluvio-glacial deposits flanking the estuary.

Accumulation of low tidal-flat deposits gave way to upper tidal-flat and marsh deposits as the transgression diminished. The transgressive event was shortlived. Sediments were deposited at the "feather edge" of the transgression. North of Creetown and the Moneypool Burn, upper tidal-flat and marsh deposits rest directly on fluvio-glacial deposits. As regression occurred, seaward progradation and incision of the carse deposits proceeded.

A pause in regression c. 2,000 years B.P. resulted in certain morphological features observed in the Cassencarie area. Stormy conditions resulted in the re-working of marginal fluvio-glacial deposits to form a spit, and to the south (between Cassencarie and Carsluith) coarse marine sands and gravels were transported landwards to form shore-parallel and oblique bars. At Carsluith, similarly-derived material forms a thinly-developed beach blanket. Recession of the sea has proceeded since 2,000 years B.P. to the present-day.

CHAPTER 1 - INTRODUCTION

1.1 GENERAL BACKGROUND AND AIMS

Evidence of Holocene marine transgression and regression in South-West Scotland is exhibited in the stratigraphical record of present and former coastal deposits. Remnant areas of Holocene coastal sediments are best preserved as flat tracts of land at the head of marine inlets along the northern shore of the Solway Firth (Figs. 1.1a & 1.1b), for example at Luce Bay, Wigtown Bay, the Nith estuary and Lochar Water. At these locations former marine sediments may extend inland for distances up to 10km, testifying to a significant change in coastal configuration as a result of marine transgression and regression during the last 10,000 years.

At the head of Wigtown Bay, former Holocene coastal deposits are well exposed along the incised meanders of the upper Cree estuary and Palnure Burn (Fig. 1.1b). A similar area of coastal sediments is present at Gatehouse-of-Fleet (Fig. 1.1c), nearer the mouth of Wigtown Bay. A particular group of coastal deposits, which include former tidal-flat, gulf and estuarine sediments, is collectively termed and frequently referred to in the literature as "carse deposits". The carse deposits are perhaps products of several different environments and sub-environments.

Jardine (1967), discussing the sediments of the Flandrian transgression and regression in South-West Scotland, distinguishes four facies - beach, lagoon, estuarine and open bay - on the basis of criteria (listed in Chapter 3.1) which are inadequate to allow complete interpretation of the depositional environments. In addition, it is difficult to sub-divide any one environment on the basis of Jardine's criteria and to separate it from other possible environments when, for example, (a) the difference in facies characteristics between two closely related environments, e.g. marsh versus tidal-flat, are subtle, especially over a small area

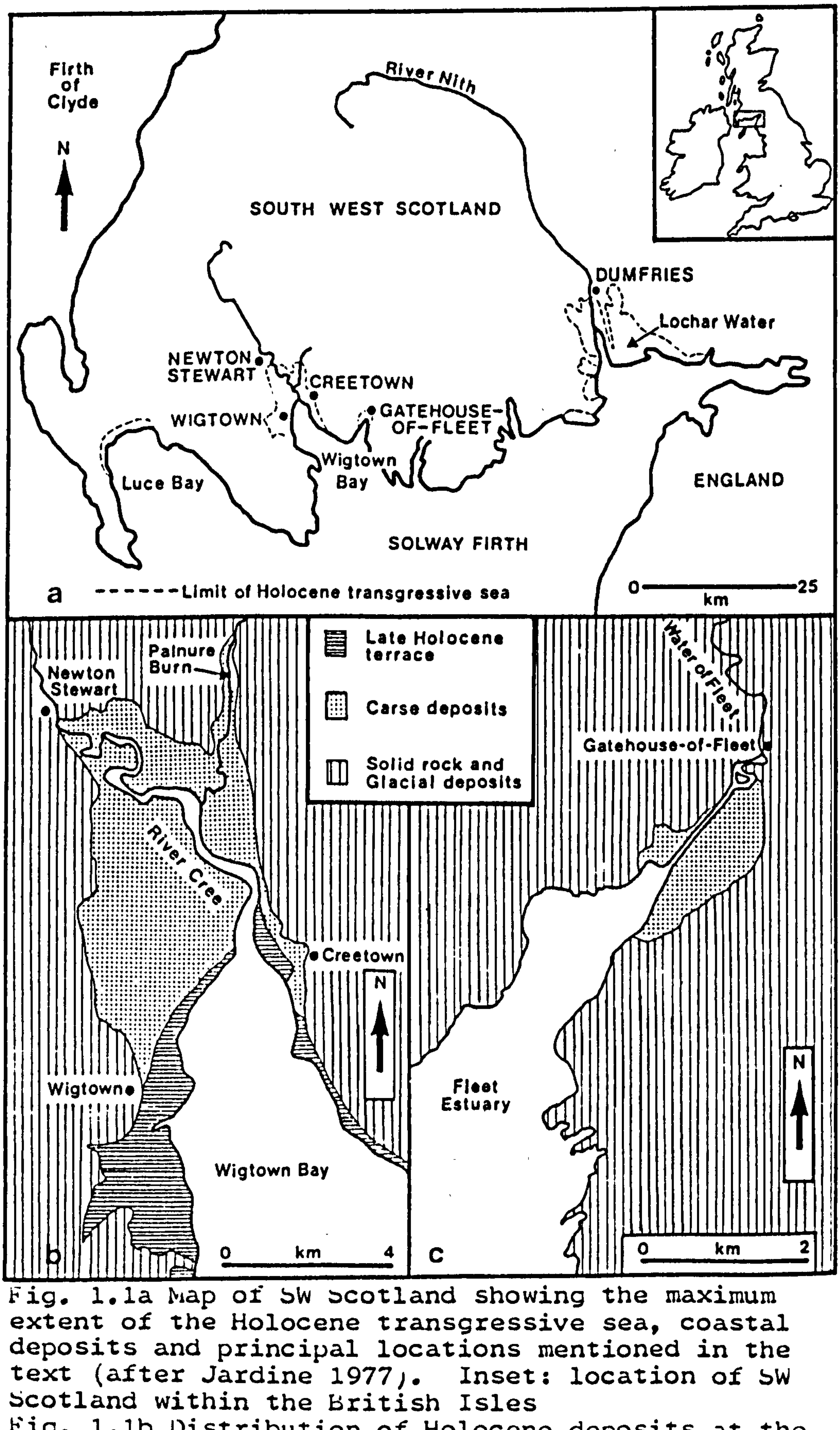


Fig. 1.1a Map of SW Scotland showing the maximum extent of the Holocene transgressive sea, coastal deposits and principal locations mentioned in the text (after Jardine 1977). Inset: location of SW Scotland within the British Isles
Fig. 1.1b Distribution of Holocene deposits at the head of Wigtown Bay (after Jardine 1975)
Fig. 1.1c Distribution of Holocene deposits at the head of the Fleet estuary, south of Gatehouse-of-Fleet (BGS 1:50 000 Drift Map)

and, (b) the evidence is sub-standard (see Chapter 3.1).

Bearing the above problems in mind, the basic aims of this study of Holocene and present-day coastal sedimentation in the Wigtown Bay area were to

1. Record, analyse and re-appraise the characteristics and sedimentary features of the coastal deposits of the Holocene marine transgression and regression.
2. Determine as accurately as possible the facies and sub-environments of deposition.
3. Attempt a palaeogeographical reconstruction of the area within a stratigraphical framework.
4. Compare the early- to mid-Holocene situation with that of the present-day environments.

1.2 GEOGRAPHICAL SETTING OF THE FIELD AREA

The field area (Fig. 1.2a), broadly encompasses the lower valleys of the River Cree and Water of Fleet, from where these watercourses assume a tidal character as defined by the Normal Tidal Limit (NTL on Ordnance Survey 1:10,000 maps) seawards to where the estuaries merge into Wigtown Bay, and finally the Solway Firth. The detailed physiography and drainage of the River Cree and Water of Fleet estuarine areas, shown in Figures 1.2b and 1.2c respectively, are described below.

1.2.1 The Cree estuary

The field area is confined to the valleys of the Cree estuary and the Palnure Burn, as delineated by a backing remnant cliff (in solid rock or glacial deposits), which marks the maximum lateral extent of penetration by the sea and northerly extension of Wigtown Bay during the Flandrian marine transgression. The southern limit of the area is defined by a SW-NE line from Eggerness Point (National Grid Reference NX 494 464) to Garvellan Rocks (NX 550 514) at the mouth of the Fleet estuary, whilst the northern boundary lies along a W-E line from

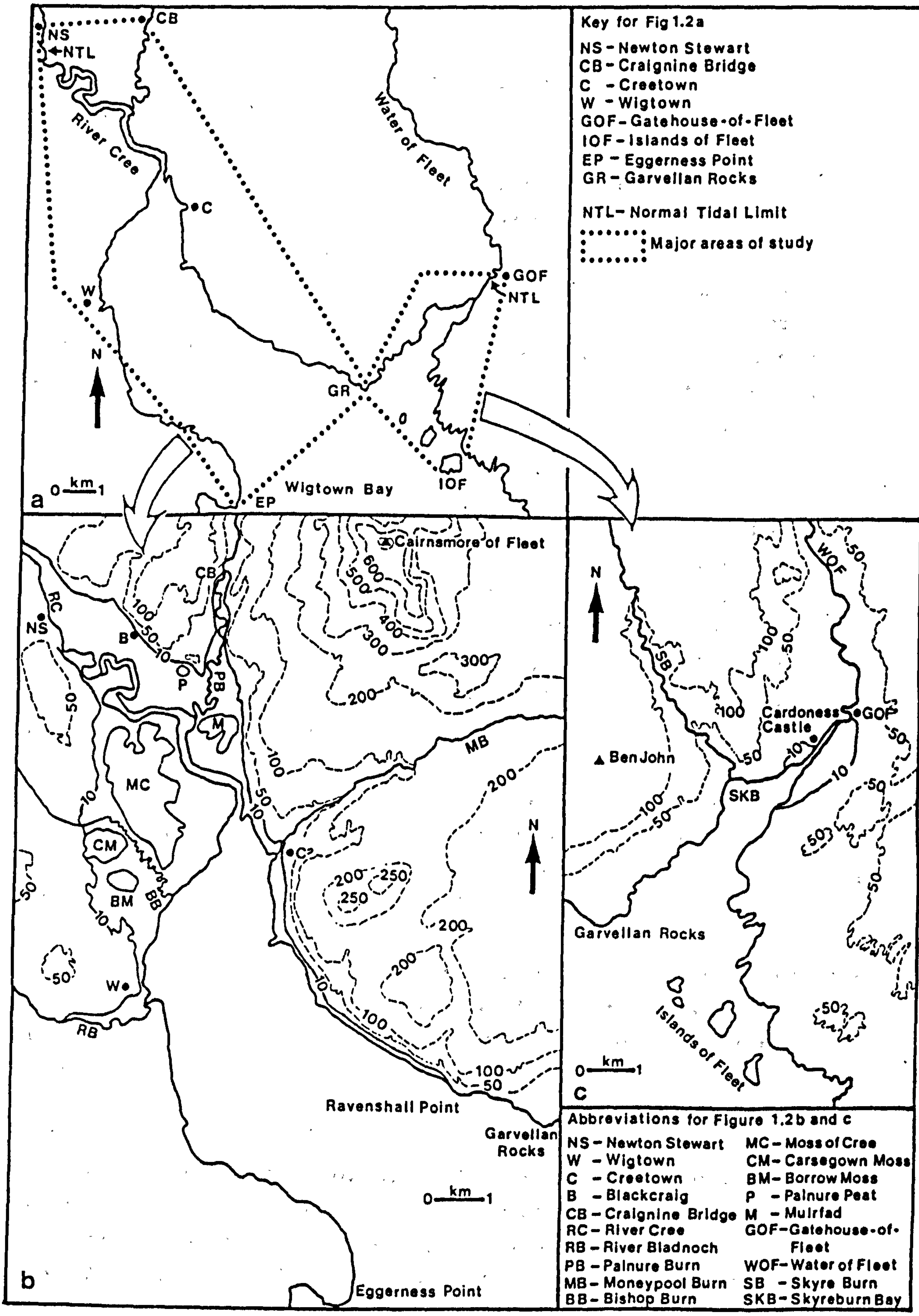


Fig.1.2a Major areas of study considered in this thesis
Fig.1.2b Physiography and drainage of the Cree estuary area
NB Numbered contours in metres. The 10m contour (solid line) is equivalent to the base of the remnant backing cliff
Fig.1.2c Physiography and drainage of the Fleet estuary area
NB Contours as in Fig.1.2b

Newton Stewart (NX 4090 6561) to Craignine Bridge (NX 4600 6631).

Along the northern margin the land rises steeply from the remnant cliff base at 10m above Ordnance Datum (A.O.D.) to over 100m A.O.D. in the vicinity of Blackcraig. East of the Palnure Burn there is a continued rise to the gently-rounded summit of the granite mass of Cairnsmore of Fleet at 711m A.O.D. South of Creetown the ground rises sharply from sea-level to over 250m A.O.D. The old cliff line lies parallel to the present coast and transects the latter at Ravenshall Point (NX 524 523).

To the south of Newton Stewart, along the western margin of the field-study area, the topography is subdued, gently undulating and rising to between 50 and 70m A.O.D. Precise limits of the margin (defined as exposure of solid rock) are obscured by a blanket of glacial deposits. However, the old cliff line re-appears NNE of Wigtown, at NX 436 558, where it borders present-day tidal-flats.

All drainage is directed towards the meandering River Cree and its estuary. Major tributaries are the Palnure Burn and the River Bladnoch. Moneypool Burn, at Creetown, and Bishop Burn, draining the western part of the Moss of Cree, are also significant. Flanking the River Cree on either side are areas of raised peat, the largest being Moss of Cree on the western bank. Nearby, to the SW, lie Carsegown and Borrow mosses. Similar, but smaller, areas of peat are located east of the river at Palnure and Muirfad.

1.2.2 The Fleet estuary

The area of interest (Fig. 1.2c) lies within a triangle whose northern apex is centred at Gatehouse-of-Fleet (NX 598 563). The western boundary extends along the shore of the estuary to Garvellan Rocks (NX 550 514), whilst the eastern boundary extends SSW towards the Islands of Fleet (NX 560 500). The Fleet estuary enters Wigtown Bay beyond a NW-SE line from Garvellan Rocks to the Islands of Fleet.

The adjacent high ground rises steeply from the rocky, low-cliffed western coast of the estuary to over 300m A.O.D. on Ben John. The SE shore is rocky in its southern half, from a point opposite Skyreburn Bay (NX 582 538) to the Islands of Fleet. To the NE of the rocky coast as far as Gatehouse-of-Fleet, the shore is backed at 10m A.O.D. by a remnant cliff (located in glacial deposits) that rises gently to 50m A.O.D. "Old" cliffs in solid rock are observable to the SW of Gatehouse, as far as Cardoness Castle (c. NX 5905 5526). The cliff with base at 10m A.O.D. borders a flat area of carse deposits, a study of which was undertaken in relation to the Gatehouse-of-Fleet By-pass (see Chapter 9).

The area is drained by the NE-SW meandering (but in part artificially-straightened) channel of the Water of Fleet and by the Skyre Burn, a NW-SE flowing tributary, entering the estuary at Skyreburn Bay.

1.3 GEOLOGICAL SETTING OF THE FIELD AREA

The area of interest is situated within grits, shales and greywackes of the Lower Silurian Gala Group, complicated by structural arrangement, intrusion and late stage mineralisation (Fig. 1.3).

Accretion of the greywacke-shale sequence, as wedges of sediment, has occurred along northerly-dipping thrust faults, such as the Pibble thrust, whose geometry is considered by Cook & Weir (1979). Structurally, the wedges young to the SE, but the stratigraphic sequence within each block of steeply-dipping beds (frequently 70°+, often vertical), ascends north-westwards. The structure and stratigraphy is explained by the imbricate thrust model, proposed for the Southern Uplands by McKerrow et al. (1977), and modified by Leggett et al. (1979). A comprehensive account of the stratigraphic setting of the rocks (in relation to the Cairnsmore of Fleet pluton) is given by Cook & Weir (1980). Weir (1968) considers the structural history of the Silurian rocks on the northern coast of the Fleet estuary, west of Gatehouse and, in a later paper

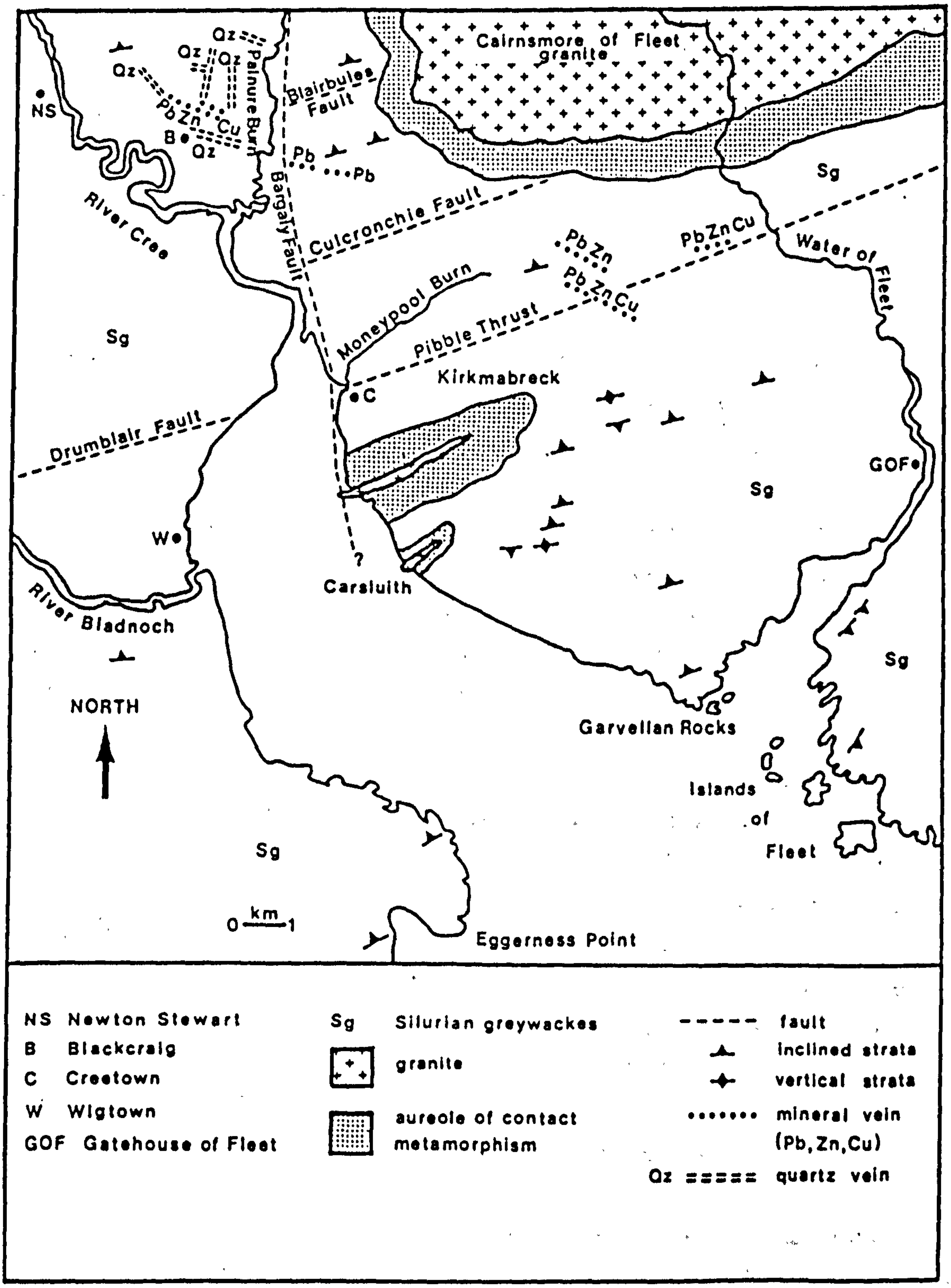


Fig.1.3 Geology adjacent to the Cree and Fleet estuaries (after BGS 1:50 000 Solid Map)

(Weir, 1974), describes the sedimentology and diagenesis of rocks in the same area.

In the vicinity of the eastern bank of the Cree estuary at Creetown, the ENE to WSW strike faults are displaced by the N to S trending Bargaly fault (Cook & Weir 1979), which extends southwards from the valley of the Palnure Burn. Blyth (1955) mentions this fault in connection with the description of the Kirkmabreck granodiorite.

Situated eastwards of, and overlooking, the Cree estuary is the Cairnsmore of Fleet granite, one of the post-tectonic "newer granites" of South-West Scotland injected, c. 392 $\pm$2 m.y.a. (Halliday et al. 1980), into Lower Palaeozoic rocks after closure of the Iapetus Ocean. The granite was first investigated by Gardiner (1937). More recently, Parslow (1964, 1968, 1971) has studied its physical and structural features and variation in its mineralogy and major elements. Work of a similar nature was undertaken by Cook (1976).

The Cairnsmore of Fleet pluton is oval in shape, 17km in length and 11km in width, its longer axis trending NE-SW, parallel to the regional strike of the country rocks. The granite ranges in composition from adamellite to granodiorite. Additionally, the intrusion has a well-developed marginal aureole of contact metamorphism, due to its emplacement into cold country rocks. Associated intrusive, granodioritic bodies are located south of Creetown, at Kirkmabreck (NX 482 563) and Carsluith (NX 485 547). These intrusions are also surrounded by well-developed aureoles.

Extensive, post-intrusive vein mineralisation is encountered around Blackcraig (NX 440 654), east of Newton Stewart. Ore minerals found together with quartz in the WNW-trending veins consist of galena, zinc, copper, chalcopyrite, baryte and mispickel. Silver and gold have also been obtained through mining, as by-products of the galena exploitation.

1.4 ORGANISATION OF THE THESIS

The text of this thesis is divided into two main parts, A and B. The four preliminary chapters provide the background setting for the work and discuss the problems to be investigated.

Part A, comprising chapters 5 to 9, is concerned with methods of investigation, sedimentological description, statigraphical interpretation and correlation, and the development of suitable palaeoenvironmental models for pre-Holocene to Holocene sediments within two major areas: the upper Cree estuary and Palnure Burn sections, north and northwest of Creetown; the lower Cree estuary sections to the south of Creetown. Summaries of the interpretations are provided at the ends of the description of both major areas.

Work of a similar nature undertaken in the Gatehouse-of-Fleet area, on the upper Fleet estuary, is discussed in Chapter 9.

Part B of the thesis deals with the present-day distribution of environments, processes and products within the Cree estuary system. Observations were based upon two independent studies, the results of which are presented and discussed in Chapter 10.

The final chapter of the thesis (Chapter 11), provides a synthesis of the work, together with recommendations for future research.

1.5 EXPLANATORY NOTES

Terms and abbreviations are explained and/or defined as follows:-

1. <u>Altitudes and elevations</u>

These are described as being Above Ordnance Datum (A.O.D.) or

Below Ordnance Datum (B.O.D.), Ordnance Datum (O.D.) being mean sea level at Newlyn, Cornwall.

The sea surface (or tide level) is recorded as Mean High Water Spring Tide (M.H.W.S.T.), and high and low water marks of spring tide are recorded as H.W.M.S.T. and L.W.M.S.T., respectively. The normal tidal limit, defined as the furthest point inland reached by a mean tide is abbreviated to N.T.L.

2. Specific locations

These are described according to the National Grid Reference system, giving the Ordnance Survey (O.S.) sheet letters (e.g. NX), followed by six or eight figure co-ordinates (eastings/northings). For example, Blackcraig is NX 440 645.

3. Radiocarbon dates

Several dates from other literature sources are quoted. Following standard practice, all radiocarbon ages quoted in the text are given in radiometric years before present (years B.P.), where "present" is AD 1950, calculated on the basis of the Libby half-life of radiocarbon (5,568±30 years, Godwin, 1962). Exact ages are quoted plus or minus (±) one standard deviation, i.e. there is a 66% chance that the age lies within the range stated.

4. Grain size classification

The sizes of sediment particles quoted are based upon a slightly modified Udden-Wentworth scale (Table 1.1), wherein the terminology used for the coarser grades of material (above 2mm) is based upon subjective judgement during field-work. The grain-size scale given in microns in the 3rd column of Table 1.1 corresponds to the sieve sizes used in sample preparation (see Chapter 4.2.1).

A description of a sediment such as "silty coarse sand with clay" denotes a sediment composed primarily and predominantly of silty coarse sand, with a subordinate amount of clay. Such terms are used informally throughout the text.

Udden-Wentworth Scale	Modified Udden Wentworth Scale	Sieve Sizes used in sample preparation
Cobble	Cobble	Maximum size cobble material retained circa 100mm long axis measurement
64mm		
Pebble	Coarse Gravel Medium	
4mm		
Granule	Fine Gravel	Fine Gravel
2mm		2mm
Very coarse Sand	Very coarse Sand	Very coarse Sand
1mm		1000μm
Coarse Sand	Coarse Sand	Coarse Sand
500μm		500μm
Medium Sand	Medium Sand	Medium Sand
250μm		250μm
Fine Sand	Fine Sand	Fine Sand
125μm		
Very fine Sand	Very fine Sand	Very fine sand
		75μm
63μm		All material below 75 dissolved during sample preparation
Silt	Differentiated in the field by chewing	
16μm		
Mud		
4μm		

Table 1.1 Terminology for grain-size classes used in this thesis (after J.A. Udden & C.K. Wentworth)

5. <u>Colour of sediments</u>

Again, as above, the estimation of the natural (unweathered) colour of a sediment is subjective. Sediment is described, for example, as being a "dark grey-blue clay", which denotes a blue clay, with a definite dark grey hue. The weathered colour of the sediment was also noted wherever possible. Where a secondary coloration was imparted to the sediment by iron staining, for example, this was stated. No formal colour guide was used.

6. <u>Occurrence frequency of organic and inorganic remains</u>

Occurrence frequency of minerals, macroscopic and microscopic plant remains, foraminifer tests, ostracod valves and macroscopic shell remains (such as bivalves and gastropods), were noted in ascending order of frequency as: rare (R), occasional (O), common (C), frequent (F), abundant (A) and very abundant (VA), according to Willis (1973). Again, these terms were applied informally in that, for example, quartz in a sample could be said to be common to very common (C-VC). The degree of shell-valve breakage, wear and disarticulation was noted informally, <u>e.g.</u> "finely crushed shell fragments", "disarticulated but unworn valves". The degree of roundness, sorting, polishing and frosting of mineral grains was also noted.

7. <u>Abbreviation of supplied borehole information</u>

The following abbreviations are included in the text where boreholes are described and discussed:-

BH, B, R, or CA denotes a borehole, usually followed by the borehole number, <u>e.g.</u> BH3. Where a letter follows the borehole number, <u>e.g.</u> BH3a, this refers to the presence of a subsidiary borehole adjacent to the original one. TP or CAP denotes a trial pit, usually followed by the trial pit number, <u>e.g.</u> TP9. Trial pits are normally shallow, to <u>c</u>. 3m in depth, and are intended as a method of preliminary investigation, prior to the siting and sinking of major boreholes.

8. Coastal and carse deposits

Coastal deposits

These include the products of at least seven individual sedimentary environments, each of which existed in the neighbourhood of the contemporaneous coast of the Solway Firth (Jardine, 1975; Jardine & Morrison, 1976).

Carse deposits

This is a collective term for a particular group of coastal deposits, including former tidal-flat/channel, marsh, estuarine or gulf sediments that now flank the northern coast of the Solway Firth, forming flat tracts of land in the lower reaches of many watercourses of the area. They are dominantly fine- to medium-grained sediments.

Merse

The term "merse", in common usage, denotes low areas adjacent to present high water mark of ordinary spring tides (H.W.M.S.T.) that are flooded periodically by storm tidal waters. The merse comprises a tract of land up to c. 100m in width, but can locally be more or less extensive, which is colonised by salt-tolerant species, and is traversed by a system of shallow tidal creeks or gullies. Occasionally, the merse merges with the high tidal-flats of the Solway Firth, but its seaward boundary is more commonly marked by a small cliff (c. 1m in height), at H.W.M.S.T.

CHAPTER 2 - QUATERNARY GEOLOGY

2.1 HISTORY OF RESEARCH

Kerr (1982) presents a general historical review of Quaternary research within the Galloway region of SW Scotland. Most of the early interest was centred on glacial phenomena. For example, Jolly (1868) wrote on "The evidence of Glacier Action in Galloway", concentrating his account upon details of landscape. The earliest map (1 inch to 1 mile) to record glacial and post-glacial features and deposits of the field area was published in 1877 by the Geological Survey of Scotland, accompanied by an explanatory text (in 1879), spanning the years of the survey from 1872 to 1878. The map, compiled by Irvine, Horne, Craik and Geikie, shows solid geology, direction of glacial striae, roches moutonées and "raised beach" (post-glacial) terraces. From the pattern of ice striae on the roches moutonées, the mappers were able to establish the direction of ice flow.

A major step forward in the understanding of glacial geology occurred in 1925 when Gregory published a paper concerning moraines, boulder clay and glacial sequence in SW Scotland. A year later, in 1926, the first authoritative account of the stages of glaciation of Galloway (and in particular the Cree valley area) was published by Charlesworth, who was also one of the first geologists to consider the changing altitude of sea-level within the context of de-glaciation of western Galloway during late-glacial times. His work was to form the basis for future glacial research within the region. Upsurge in glacial research during the first 25 years of this century led to the improvement of sedimentary techniques and the production of better quality base topographic maps by accurate surveying methods. Subsequently, the increasing knowledge of the distribution of glacial and post-glacial deposits was reflected in the extensively revised 1925 edition of the 1 inch to 1 mile Wigtown map sheet, compiled by Peach & Horne, who differentiated between glacial deposits and solid geology, a fact not considered in the first edition. In 1981, the

1:63,360 scale maps were replaced by 1:50,000 scale sheets, the solid and drift deposits being published in separate editions. The spatial distribution of deposits remains unchanged from the previous edition, the main difference being a refinement of the positions of the margins of the deposits.

Between the 1930s and late 1950s, glacial and post-glacial research interest was static. Since then, however, there has been an explosion of multi- and interdisciplinary papers on post-glacial deposits, shorelines, relative movements of sea-level, and vegetational studies.

A review of late-Devensian environments in South West Scotland is provided by Bishop & Coope (1977). Palynological work undertaken by Nichols (1967), Moar (1969) and Birks (1972a), provides a good basis for the interpretation of the colonisation pattern of vegetation and its development during the first 5,000 years of the post-glacial period.

The early post-glacial period in Scotland (c. 10,000 to 5,000 years B.P.) is represented by sediments of the Flandrian (Holocene) marine transgression, an inundation brought about by the rise in sea-level caused by the melting of the final remnants of Scottish as well as world-wide ice. This was followed by a period of marine regression from c.5,000 years to the present day.

The limit of the Holocene transgression is the main post-glacial shoreline, which, due to subsequent regression, is expressed as raised platforms and sand and gravel beaches or as raised estuarine flats known as "carselands". The former, located on the west coast of Scotland, have been studied by McCann (1961a, 1964, 1966) and Synge & Stephens (1966). The levels of the "carselands" that occur in the sheltered firths of Forth and Tay have been examined by Sissons (1962, 1963, 1966), Cullingford & Smith (1966) and Sissons, Smith & Cullingford (1966).

Early work regarding changes of sea-level within the Solway Firth area was undertaken by Donner (1963). He recorded evidence for the Holocene transgression at seven sites along the Solway Firth and discussed his findings in terms of a "Late-Glacial 100' beach" and a "post-glacial 25' beach".

However, deposits and events of the Holocene transgression along the northern shore of the Solway Firth are discussed mainly by Jardine in a series of papers (1962, 1964, 1967, 1971, 1975, 1977, 1980, 1982) which constitute the background to this research.

2.2 QUATERNARY GEOLOGY OF THE FIELD AREA

The earliest account of glacial and post-glacial deposits of the study area is by Geikie (1879), in the Memoirs of the Geological Survey of Scotland, in which he erroneously mentions the absence of organic remains in the "brick" (or carse) clays. Glacial and non-glacial deposits are described under the headings of "drift", "raised beaches", "alluvium and peat".

The extent and distribution of glacial and post-glacial deposits within the study area, shown in Figure 2.1a and 2.1b, is based upon the Wigtown and Kirkcudbright 1:50,000 drift maps, with certain modifications and additions by the writer. For clarity, the extent and distribution of present-day estuarine deposits are omitted but are considered in Chapter 3.2.

2.2.1 The Cree estuary

During the last "main" Devensian glaciation the area was scoured by ice originating on the high ground to the north (Merrick). The ice moved down the Cree valley southwards to Wigtown before meeting ice travelling in a SW direction from Cairnsmore of Fleet. The two ice streams then continued in a SW direction.

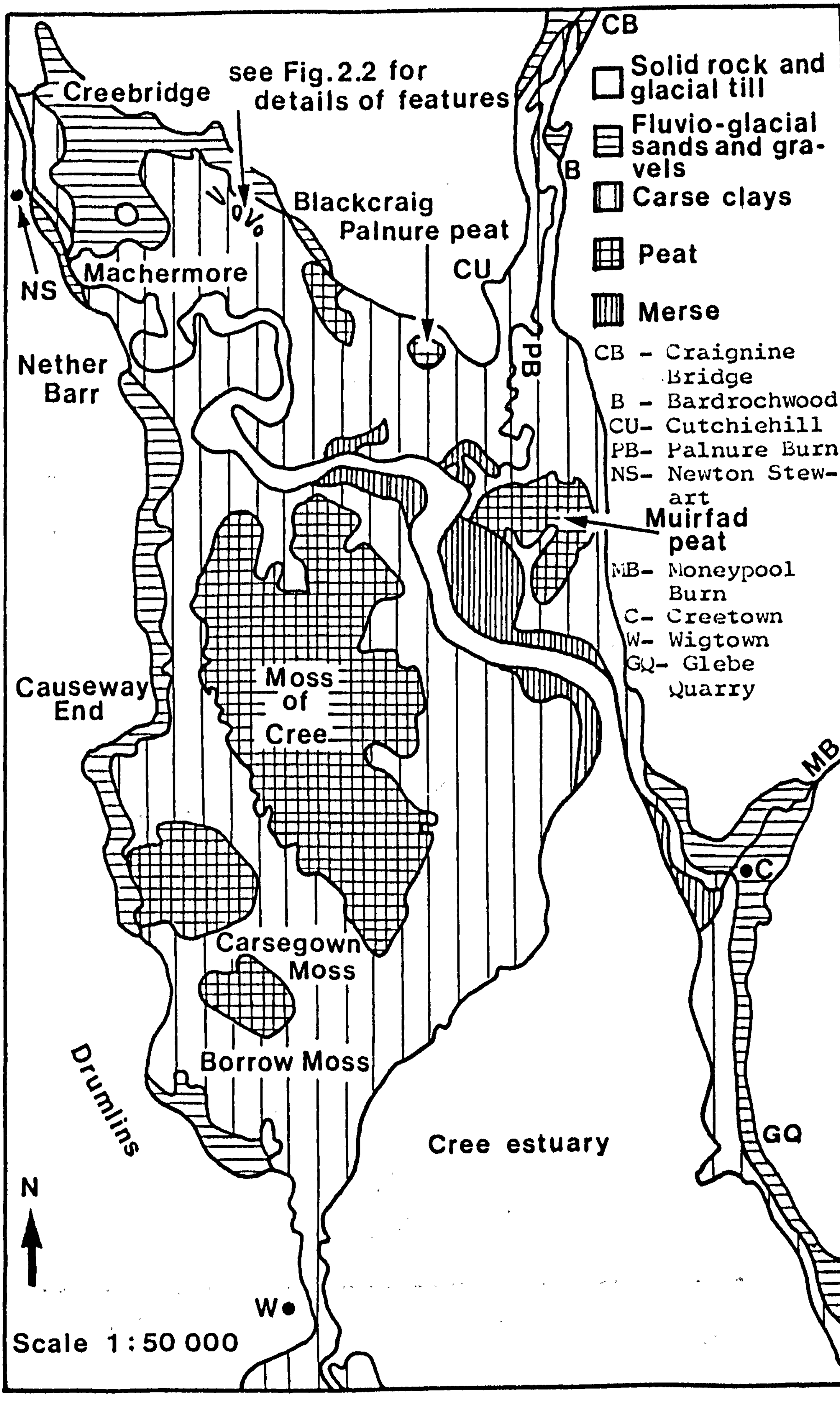


Fig.2.1a Distribution of Quaternary deposits in the Cree estuary area (after BGS 1:50 000 Drift Map and writer's maps)

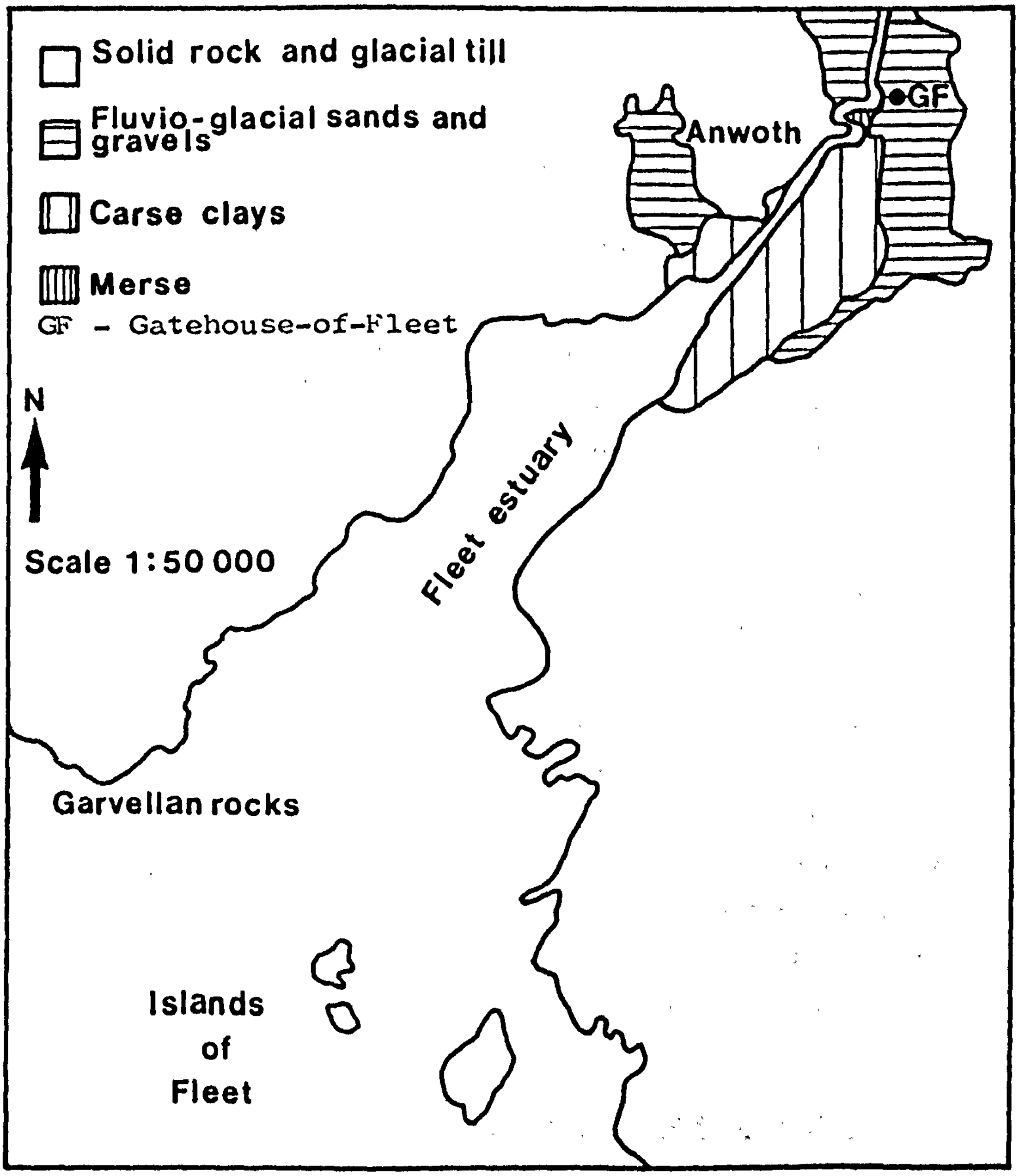


Fig.2.1b Distribution of Quaternary deposits in the Fleet estuary area (after BGS 1:50 000 Drift Map)

Deposits resulting from the glaciation consist of lodgement till, a firm tenacious clay with rounded pebbles and cobbles, deposited during the glacial advance, and later fluvio-glacial outwash, roughly stratified and sandier than the till, with large boulders deposited during the melting of the ice.

The till has a restricted distribution at surface, in the following areas:-

<u>Causeway End (NX 4217 6029)</u>

A roadside exposure, <u>c</u>. 1 to 1.50m in length by <u>c</u>. 2m in height, consisting of buff grey, poorly-sorted, clast-supported "conglomerate", with a patchy clayey matrix.

<u>Drumlinoid forms, Wigtown area (e.g. NX 4286 5635, NX 4261 5580, NX 4186 5546)</u>

These constitute low hills, <u>c</u>. 15 to 25m in height, with a consistent NW to SE elongated trend parallel to ice flow direction. A full account of drumlins in the Wigtownshire area is given by Cutler (1979).

Additionally, till is found in boreholes from Creetown to Carsluith, on the eastern side of the Cree valley (Chapter 7).

The fluvio-glacial outwash deposits are widely distributed throughout the area at surface, forming elongated kame terraces of varying width and length at the margins of the Cree valley and Palnure Burn areas and also as sheet-like "spreads" of material in the Cree valley between Newton Stewart and Blackcraig. The fluvio-glacial deposits are indicative of climatic amerlioration. They are distributed as follows:-

<u>Nether Barr (NX 4208 6334) to Wigtown (NX 4345 5617)</u>

The fluvio-glacial terrace has a beaded appearance, forming a discontinuous strip between the above locations. Its western margin rests on glacial till or solid rock. Its eastern margin is overlapped by the carse clays. The deposits consist of well-stratified, sorted sands and gravels of variable thickness. At the northern end of the area, bare rock protrudes through the thinned covering at Upper Barr (NX 4221 6322) and east of Lamachan View, at NX 4261 6272. Near Wigtown (NX 4345 5617), the terrace terminates against "headlands" of a former rocky shoreline formed prior to the late-glacial period of higher sea-level.

Creebridge (c. NX 4170 6560) to Machermore Castle (NX 4176 6445)

Between the above-named locations a tongue-shaped spread of typical sand and gravel deposits with cobbles lies at c. 15 to 30m A.O.D. Thickness is not consistent as solid rock projects above the terrace surface in several places, e.g. at Craggyrounal Plantation (NX 4210 6482). North of Machermore Castle at NX 4181 6462 the surface of the terrace is punctuated by a kettle hole known as the "Punch Bowl". It is c. 12m in depth and 130m in diameter.

In the area immediately east of Mains of Machermore (NX 4237 6460) and north of Machermore Cottages (NX 4262 6480) a broad embayment is present at the margin of the terrace (Fig. 2.2). Deposits here thin from NW to SE due to reworking of the terrace margins by the Holocene marine transgression. Ridge (spit?) features are evident SW of Calgow Farm at NX 4280 6503 and SE of the farm at c. NX 4312 6471. Additionally, a borehole sunk at NX 4242 6509 as part of a preliminary survey for the Newton Stewart By-pass revealed 9.90m of relatively coarse (sandy), laminated deposits believed to represent kettle hole infill material.

Calgow (NX 4350 6512) to Blackcraig (NX 4398 6428)

Two narrow, steep-fronted terraces lie at c. 10 to 20m A.O.D. between the above-named locations. The deposits consist of typically well-rounded cobbles and occasional boulders set in a matrix of finer-grained, orange-coloured sands and gravels.

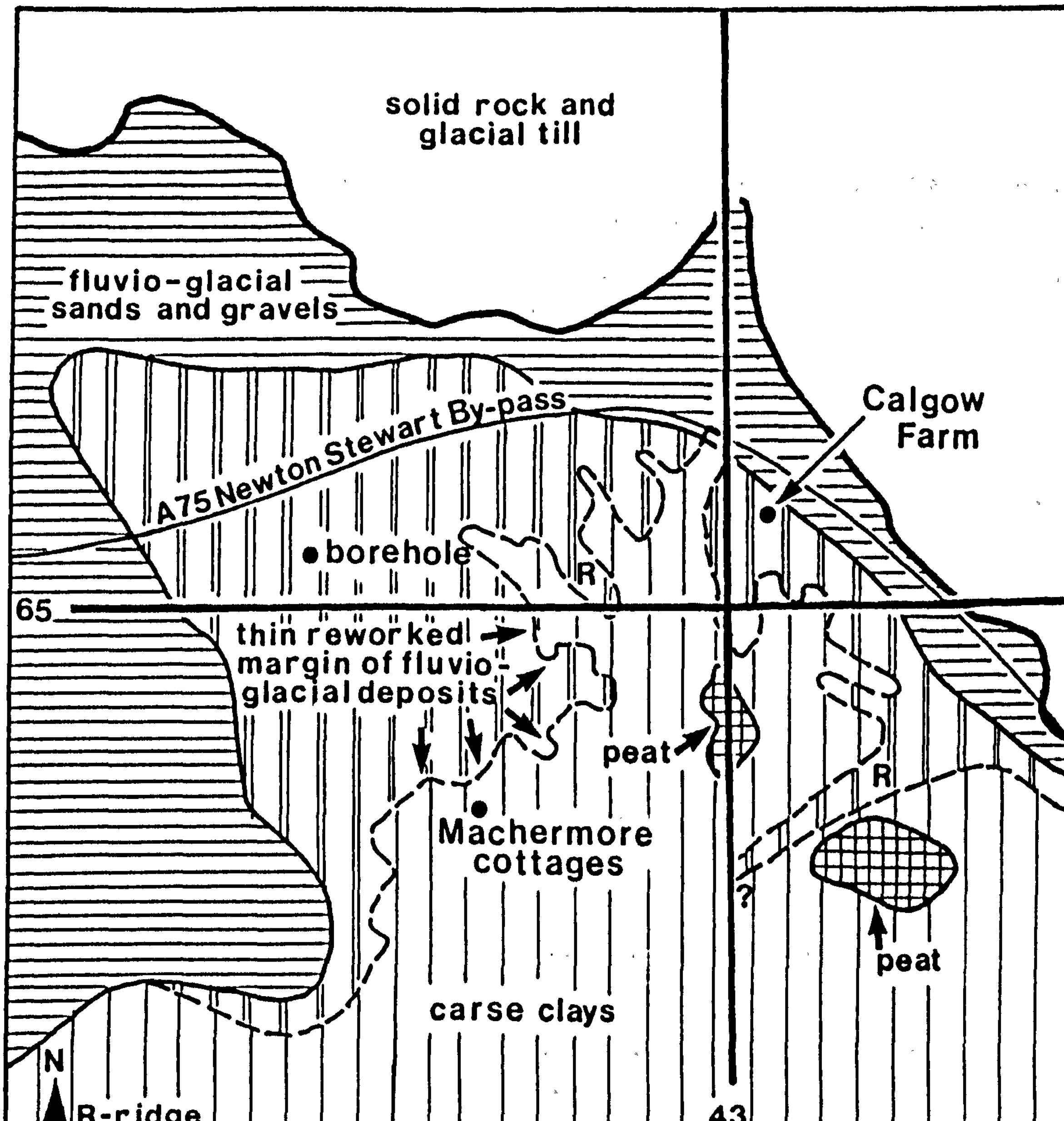


Fig.2.2 Ridge features at Calgow, SE of Newton Stewart

Palnure Burn area

Craignine Bridge (NX 4600 6635)

Flanking the Palnure Burn immediately east and SW of Craignine Bridge are locally-extensive fluvio-glacial terraces, extending from c. 10 to 20m A.O.D. To the SW of the bridge, the terrace extends as far as Little Park Farm. The extent of the eastern terrace was not established.

Bardrochwood (NX 4610 6528)

A thick development of fluvio-glacial deposits chokes the valley of Mill Burn as it enters the valley of the Palnure Burn at Bardrochwood. A small triangular-shaped hollow NW of Woodend Bridge, at location NX 4597 6544, is possibly a kettle hole.

Cutchiehill (NX 4540 6440)

A tongue-shaped deposit of sand and gravel infills the narrow valley of the Bruntis Burn as it enters the valley of the Palnure Burn from the west.

Pulwhat (NX 4641 6146) to Creetown (NX 4718 5800)

Fluvio-glacial outwash deposits are observed at surface and recorded in boreholes between the above-named locations. Galloway (1961) noted the occurrence of ice-wedges and involutions at Pulwhat, which implies the temporary existence of periglacial conditions after deposition of the outwash, possibly during the Loch Lomond Stadial (c. 11,000 to 10,000 years B.P.). An account of the nature of the fluvio-glacial deposits encountered in the boreholes is given in Chapter 7.1, in discussion of evidence obtained in the course of development of the A75 Creetown By-pass.

Glebe Quarry (NX 4781 5636) to Carsluith (NX 4918 5445)

The fluvio-glacial sands and gravels are seen at the surface at two localities, now described.

An exposure at the entrance to Glebe Quarry (NX 4790 5640) is approximately 5m in length by 2m in height, at 12 to 14m A.O.D. It exhibits a generally coarsening-upward sequence of roughly-stratified, loosely-consolidated and intertonguing units of sand and gravel. No cross beds are recorded. Occasional individual units exhibit small-scale upward coarsening, confirming the trend for overall upward coarsening. Units are poorly-sorted, matrix-supported conglomerates, with occasional intra-unit lenses of clast-supported material.

At the junction of the old A75 road and the By-pass (location NX 4918 5445), approximately 5m of poorly-sorted, upward-coarsening sands and gravels rest directly on fine greywacke sandstone with a slaty cleavage, dipping steeply (c. 85° to 90°) to the NW. Large (up to c. 0.50m diameter) boulders of local granite are observed in the top 1 to 2m of the sequence.

Fluvio-glacial deposits are also recorded from boreholes along the line of the A75 Carsluith By-pass (Chapter 7.6), and are well described from White Hill.

<u>Holocene events and deposits</u>

Sea-level was relatively low at the close of the Devensian late-glacial Loch Lomond stadial around 10,000 years B.P. By c. 8,500 years B.P., however, the rate of rise of global sea-level had begun to outpace the regional rate of rise of the land so that the Flandrian marine transgression took place in the North Sea and Irish sea areas. In the course of the transgression, the sea flooded the area of the Cree estuary, encroaching upon the fluvio-glacial deposits to rework the margins. Deposition of fine- to medium-grained carse clays ensued, the carse deposits overlapping onto the margins of the fluvio-glacial deposits, infilling hollows in the kame terraces and generally evening out irregularities in the late-glacial topography.

The transgression initiated a number of changes, considered in Chapter 3.2. The carse deposits comprise clays and silts, interstratified with sands and gravels, shell remains and organic debris.

During deposition of the carse clays, rapid shifting of environments led to the constant reworking of sediment within the estuary, e.g. the reworking of kame terrace deposits into gravel bars in the vicinity of Calgow (NX 4280 6503, NX 4312 6471).

Regression of the sea c. 5,000 years ago led to the formation of coastal marshes and peat, the progradation of tidal-flats and general infilling of the estuary. In certain parts of the Cree estuary there is a record of late- Holocene estuarine beach deposits (Chapter 7.4, 7.6) that formed under temporary transgressive conditions due to a pause in regression.

2.2.2 The Fleet estuary

A full account of glacial and fluvio-glacial deposits flanking the Fleet estuary south of Gatehouse-of-Fleet (Fig.2.1b) is given in Chapter 9, in relation to the development of the A75 Gatehouse-of-Fleet By-pass. The distribution of other deposits is not considered here.

Fluvio-glacial terraces of limited extent flank the area of interest south of Gatehouse-of-Fleet. Sands and gravels choke the valley south of Anwoth, at location NX 5840 5540, whilst the western margin of the fluvio-glacial terrace in a NE to SW line from Gatehouse-of-Fleet is cliffed due to reworking by the subsequent Flandrian marine transgression, prior to deposition of the overlying carse clays.

CHAPTER 3 - EARLY-HOLOCENE TO PRESENT-DAY ENVIRONMENTAL SETTING

3.1 PRINCIPLES AND PROBLEMS

The sediments of the Flandrian transgression in South West Scotland, may be subdivided into four facies - beach, lagoon, estuarine and open bay - on the basis of the following criteria (Jardine 1967):

1. Shape of sedimentary body
2. Location of sedimentary body in relation to contemporary shoreline
3. Texture
4. Sorting
5. Stratification
6. Organic content

Theoretically, the above criteria should be adequate to allow a definite environmental interpretation and the assignation of a particular facies to a depositional environment to be made. Unfortunately, due to complications now discussed, this is not so.

Although the carse clays of the field area have been attributed to an estuarine or tidal-flat origin, none of the previously-mentioned criteria appears to successfully or completely define the presence and location of an estuarine or tidal-flat environment and its associated sub-environments. This is partly because there is a lack, or limited evidence, of the criteria, as a result of changing sedimentological conditions through time, and partly because there is an uneven distribution of suitable sections within the field area.

The acquisition of data (Chapter 4) was restricted to suitably incised river-bank sections and boreholes in the area at the head of the Cree estuary and Palnure Burn (Fig. 3.1), together

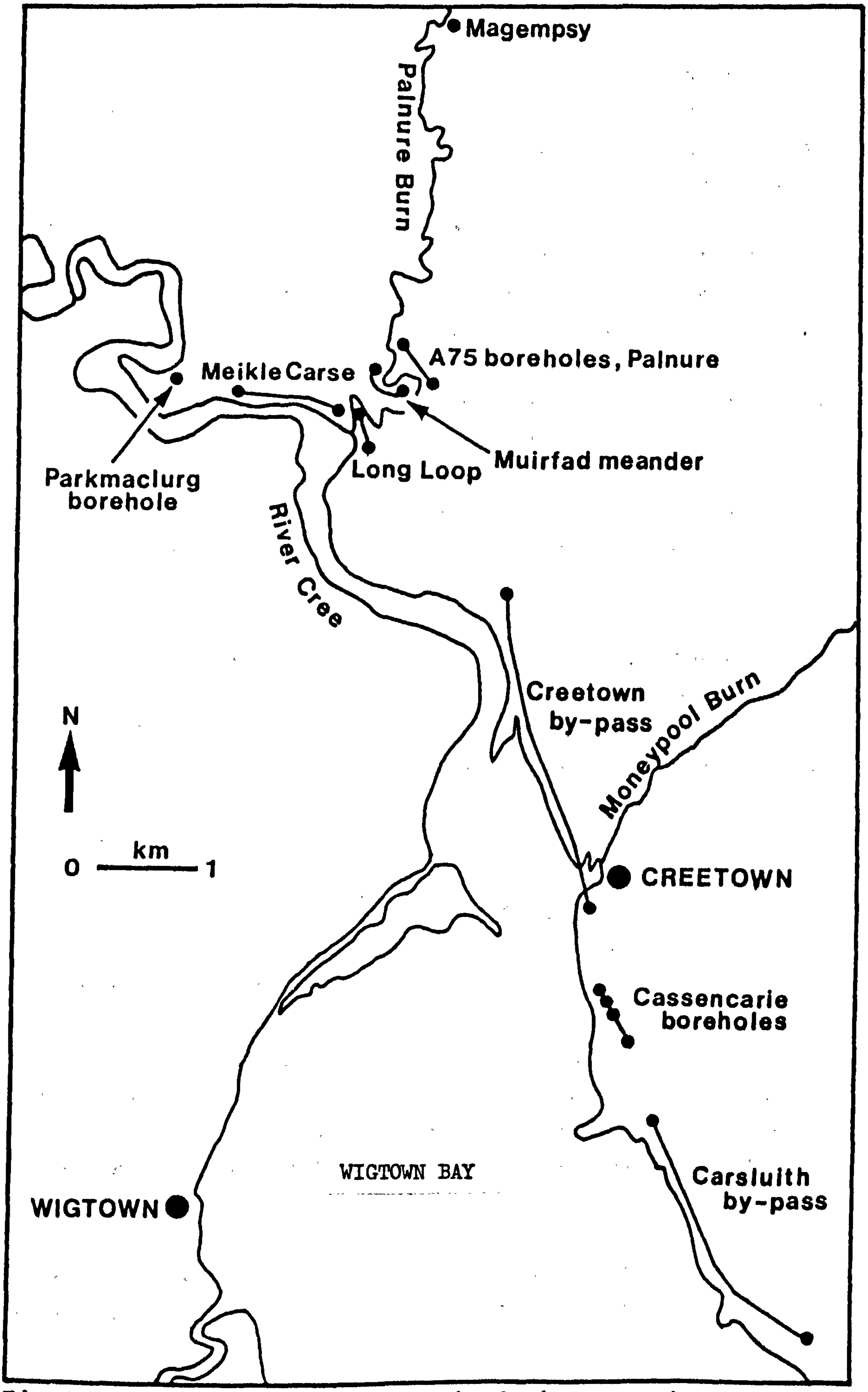


Fig.3.1 Location of studied incised river sections, bore-holes and by-passes

with information obtained via civil engineering consultant companies concerned with by-pass construction and road improvement schemes along the A75 trunk road. The information acquired is, therefore, heavily biased to the head of the Cree estuary and its eastern flank. It is possible to gain a fairly accurate picture of environments and events in the aforementioned area, but to the west, in the area south of Newton Stewart as far as Wigtown, a similar degree of accuracy cannot be achieved due chiefly to the fact that there are no stream sections incised into the carse clays of that area. This problem has not been resolved, and will not be resolved until major excavations are made and exploratory boreholes are drilled, either in the course of road construction or in a research scheme manned and financed at a level well beyond the scope of the project discussed in this thesis. It follows that certain assumptions have had to be made regarding the palaeoenvironments of the area to the west of the present Cree estuary.

The major problem concerning the elucidation of palaeoenvironments in the area of the Cree estuary during the Holocene Epoch is strictly sedimentological in nature, stemming from a change in the nature of sediment type and in changing patterns of sedimentation since the end of Lateglacial times.

Deposition in the palaeo-Cree estuary from c. 10,000 years to 5,000 B.P. was dominated essentially by fine-grained sediments - muds and silts, with relatively subordinate amounts of coarser-grained sediment concentrated in certain subenvironments (e.g. the channel environment). The dominance of fine grades is accompanied by a lack of characteristic sedimentary structures, vital to the recognition of palaeoenvironments. Additionally, there is a lack of supporting criteria, e.g. faunal.

Consequent upon marine regression from c. 5,000 years to the present-day, with infilling and maturing of the estuary, the grade of material being deposited became coarser. Sedimentary structures typical of a particular environment or sub-environment were formed and are easily recognised.

The solving of the problem of the natures and identities of the palaeoenvironments that existed in the study area, therefore, lies in the finding of suitable sedimentary structures in the palaeo-Cree estuary and, using the limited evidence available, in making comparisons with similar present-day environments in which sedimentary structures are clearly observable.

Boscence (1973), albeit working on Eocene sediments of the London Basin rather than Holocene and present-day sediments, recognised the nature of what he termed the "estuarine problem". Although identifying bimodal parameters (typical of a tidal situation), a simple marine tidal assignation of the beds he was studying was impossible because of the lack of fossils and rarity of burrows. An estuarine environment was possible but not proved on the basis of the available evidence. A similar problem exists in the case of the area of the Cree estuary and Palnure Burn. Conclusions regarding the sequence require to be based in part on the absence of evidence.

Because it is difficult to establish the presence of a particular environment or sub-environment on the basis of lack of sedimentary structures, burrowing etc. when considering any given sedimentary facies of the study area, it is even more difficult to separate the environment concerned from adjacent environments. Frequently the differences in characteristics between a tidal-flat and a marsh are subtle and widely variable, and they are assessed subjectively. In addition, because the nature of a particular sedimentary body cannot be readily determined, it is virtually impossible to recognise the relationship between the shape of that sedimentary body and the corresponding shoreline position. This in turn hampers palaeogeographic reconstruction.

To resolve these problems, detailed attention must be paid to lateral changes in facies and to juxtaposition of environments.

Methods of resolving the aforementioned problems are summarised within the listed aims of the study (Chapter 1.1). Problems concerned with comparison of early- to mid-Holocene situations with those of present-day environments (aim 4) are best considered within the context of the early-Holocene to present-day environmental setting of the study area, discussed below (Chapter 3.2).

3.2 PRESENT-DAY AND EARLY-HOLOCENE ENVIRONMENTS

In order to understand the distribution of early- to mid-Holocene estuarine environments and sub-environments in comparison with those of their present-day equivalents, it is necessary to discuss the latter. The present-day distribution of estuarine environments is shown in Fig. 3.2 and the major characteristics of each environment are summarised in Tables 3.1 and 3.2. The major environments and sub-environments of the Cree estuary are now considered.

3.2.1 The upper Cree estuary

Introduction

The River Cree presently flows in a NW to SE direction through the earliest infilled part of the Holocene estuary. The Cree is classed as estuarine-fluvial in character between its NTL and Creetown. It is deeply incised and meandering, as a result of responding to rapid withdrawal of the sea from the area, the river cutting down to base level quickly. The tightly curved meanders are flanked by well-developed point-bars. Channel-floor braid-bars appear at times of low water. There is development of flanking intertidal merse in a seawards direction.

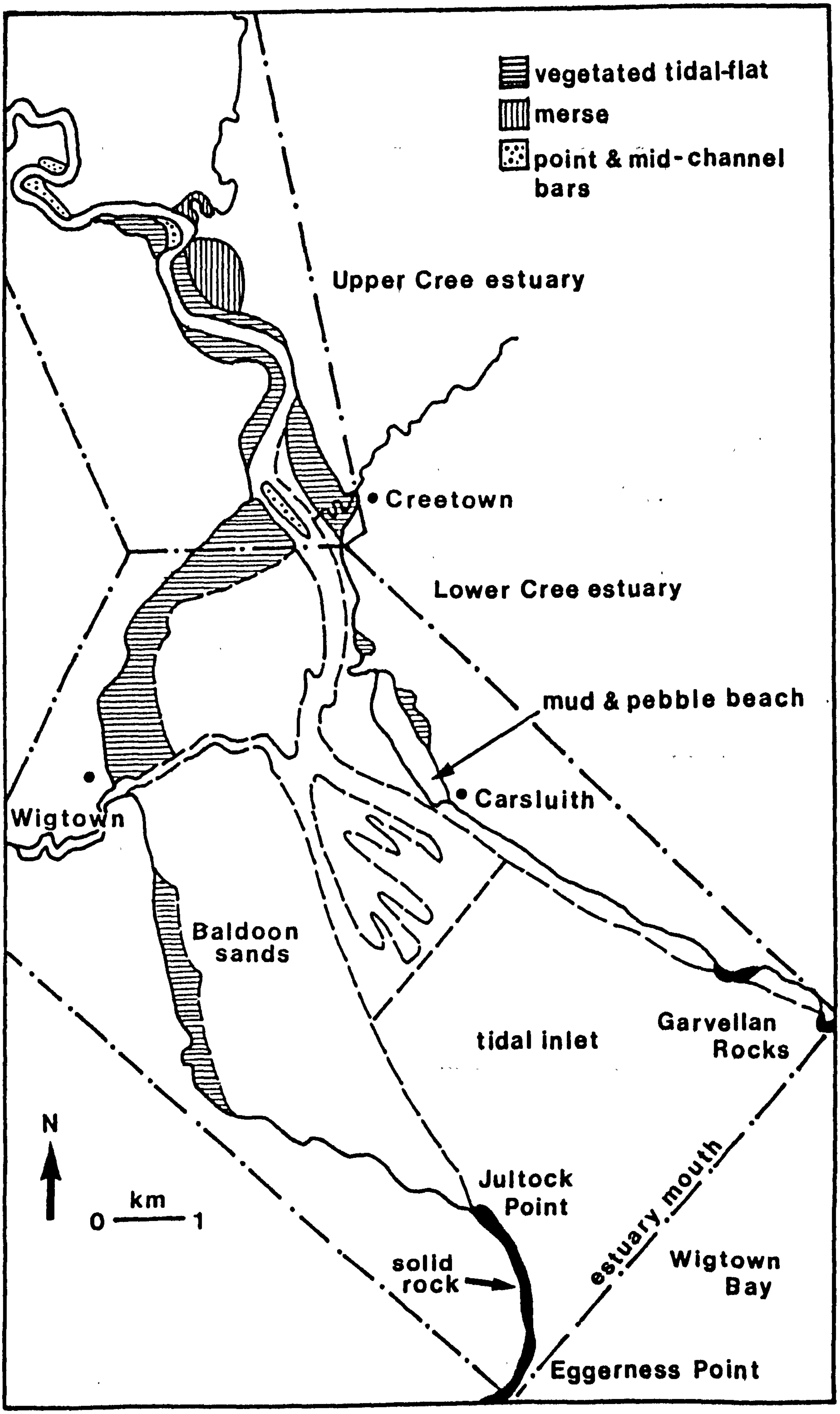


Fig.3.2 Present-day distribution of estuarine environments

Location	Bottom morphology	Sedimentary facies and environment	Dynamic environment
Upper Cree estuary estuarine-fluvial from the normal tidal limit (NTL) to Creetown.	Deeply incised, meandering river type. Well developed point-bars of varying scale. Channel-floor braid bars at low stage. Development of flanking intertidal merse seawards.	Channel-floor: (a) lag of shells, pebbles, twigs and leaves (b) mid-channel and side-bars of coarse sand Channel flanks: convex banks of structureless, silty muds Point-bars: muddy silt, sand alternations (upper point bar), sandy silt to medium-grade sands (lower point-bar) Intertidal flats and flanking merse: clay, silt, grass and marsh alternations. Dissection of flats by tidal-creeks. Extensive lateral migration.	Alluvial currents attenuated by very strong tidal flow. Tidal flow increases in dominance towards Creetown *i.e.* seawards.

Table 3.1 Present-day environments of the upper Cree estuary

Location	Bottom morphology	Sedimentary facies and environment	Dynamic environment
Lower Cree estuary (Creetown to NE/SW line, Eggerness Point to Garvellan Rocks)			
i Creetown to Carsluith	Bifurcation of single channel. Development of intertidal banks.	Intertidal shoals/banks: composed of sandy mud and fine- to medium-grade sand. Intertidal mudflats: composed of muddy sand/sandy mud - coarsening to channel. Dissected by tidal-creeks. Vegetated at their W margin. E bank exhibits narrow mud and pebble estuarine beaches.	Tidal current dominance with ebb/flood differentiation.
ii South of Carsluith to estuary mouth	Marine coastal morphology. Development of beaches, rocky, cliffed shore.	Tidal sand ridges composed of coarse sands.	Interaction of tidal currents and waves.

Table 3.2 Present-day environments of the lower Cree estuary

Present-day environments: lithofacies, sedimentary features and dynamic energy

1. Channel-floor

Deposits are medium to coarse sands and fine gravels exhibiting low-angle herringbone cross stratification and uni-directional (chiefly flood-oriented), small to medium scale ripples, bearing frequent reactivation surfaces. There is also abundant lag material of disarticulated shell valves (mostly *Cerastoderma edule*), small pebbles, twig, leaf and grass remains. No burrowing is evident. The deposits are fashioned into channel-floor bars which migrate periodically. Deposition of fine-grained sediment (*i.e.* muds and silts), from suspension, occurs on the convex channel flanks. The muds are structureless. There is some patchy bioturbation by present-day bivalves and the amphipod *Corophium volutator*. Extensive undercutting of channel flanks occurs along the River Cree and Palnure Burn, resulting in large-scale rotational slumps.

2. Point-bars

The well-developed point-bars show a typical fining-upward laminated sequence, grading from medium sand on the lower point-bar to sandy, silty fine sand and alternations of sand and silt on the upper point-bar. Flood-oriented ripples predominate.

3. Intertidal flats and flanking merse

Deposits are of laminated clay, silt and fine sand interbedded with grass wisps and leafy vegetable matter. The intertidal flats and flanking merse are dissected by meandering tidal-creeks. The merse merges with the intertidal flats near Creetown.

Dynamic environment

The dynamic environment of the upper Cree estuary is one of fluvial currents attenuated by very strong tidal flow whose dominance increases seawards. Fluvial dominance is only evident during periods of high river discharge.

Early- to mid-Holocene environments

Examples of the Holocene equivalents of the afore-described present-day environments are summarised in Table 3.3, and are now discussed (see also Chapter 5).

1. Channel-floor/point-bar lag material

Examples of herringbone cross-stratification recorded in coarse-sand box cores at Carsenestock are similar to examples observed in the Meikle Carse section. Channel-floor lag material is evidence of a channel-floor or basal point-bar environment. Equivalent Holocene examples are exhibited at Blackstrand, where there is a well-developed basal point-bar lag, on the Palnure Burn Muirfad meander section, where the situation is further complicated by channel-margin slump activity, and at the mouth of the Palnure Burn (Long Loop section) where the lag is not so well-developed. As with the modern examples, there is no evidence of burrowing since the energy of the environment was too unstable (i.e. it fluctuated too frequently) to permit colonisation by organisms.

2. Large-scale channel-floor bars

There is limited evidence for the existence of discontinuous bars in the Meikle Carse section, probably due to the fact that the bulk of the material being deposited was very fine in grade; coarse-grade clasts suitable for the formation of bars were not available in this area. Good examples of bars formed in coarse gravel and very coarse sand were recorded in the basal parts of logs in the Muirfad meander section.

3. Convex channel flanks

Holocene equivalents of convex channel flanks were not obvious, possibly because banks with a high degree of convexity were not forming in the past; banks may have been larger in scale and less-steeply sloping. There is evidence at Blackstrand and at the eastern end of the Meikle Carse section of a steeply

Present-day environments	Equivalent Holocene environments and their location
Upper Cree estuary	
1. Channel-floor	1. Channel-floor/point bar lag material - Meikle Carse section, Muirfad meander section & Long Loop section
2. Channel-flanks	2. Channel flanks - Meikle Carse section
3. Point-bars	3. Point-bars - Meikle Carse section & Muirfad meander section
4. Intertidal flats & flanking merse	4. Intertidal flats & flanking merse - Meikle Carse section
	5. Meandering tidal creeks & associated channel-margin slumps & point-bar front slumps - see Table 3.4
Lower Cree estuary	
1. Intertidal shoals & banks	1. no equivalent
2. Intertidal mudflats	2. Intertidal mudflats - Meikle Carse section
3. Tidal inlet	3. no equivalent
4. Estuarine beaches	4. Estuarine beaches - between Creetown & Carsluith

Table 3.3 Comparison of present-day and Holocene environments

convex bank in association with a point-bar front. The steep point-bar fronts have been subject to slumping. A convex point-bar is recognised as being such when its lateral relationship with a tidal channel-infill is considered.

4. Point-bars

Presumably point-bars were of varying size in the past as they are at present. It is difficult to establish the presence of large-scale point-bars in the older sequence due to the lack of suitable sections and the immensity of the point-bars. It is possible, however, to locate meander scars, and hence adjacent point-bars, on aerial photographs (Fig. 3.3). The best examples of point-bar development were recorded at Blackstrand, at the eastern end of the Meikle Carse section, and at Muirfad meander. It is suspected that the last example is in fact large-scale because of the low angle of the lateral accretion surfaces. There is no evidence of this on aerial photographs.

5. Development of intertidal flats

Comparison is made with the present intertidal area adjacent to the Moneypool Burn at Creetown (see Chapter 10.3.2.1 and 10.3.2.2). The tidal-flat at Creetown consists of a series of zones, extending seawards from unvegetated mudflat through mixed mud/sand flat to sandflat. Due to the general lack of coarse-grade sediment in early- to mid-Holocene times, there is no real evidence of an equivalent of the above-mentioned zonation. Nearly all of the former intertidal flat deposits are composed of silt and mud. This suggests a lack of supply of coarse detritus (possibly it was retained as traction load in adjacent tidal-creeks) and a much greater supply of fines, from a source different from today's material.

Broad expanses of intertidal flats are thought to have existed in the vicinity of the Meikle Carse section. Thinner sequences of intertidal flat deposits were recorded in all sections.

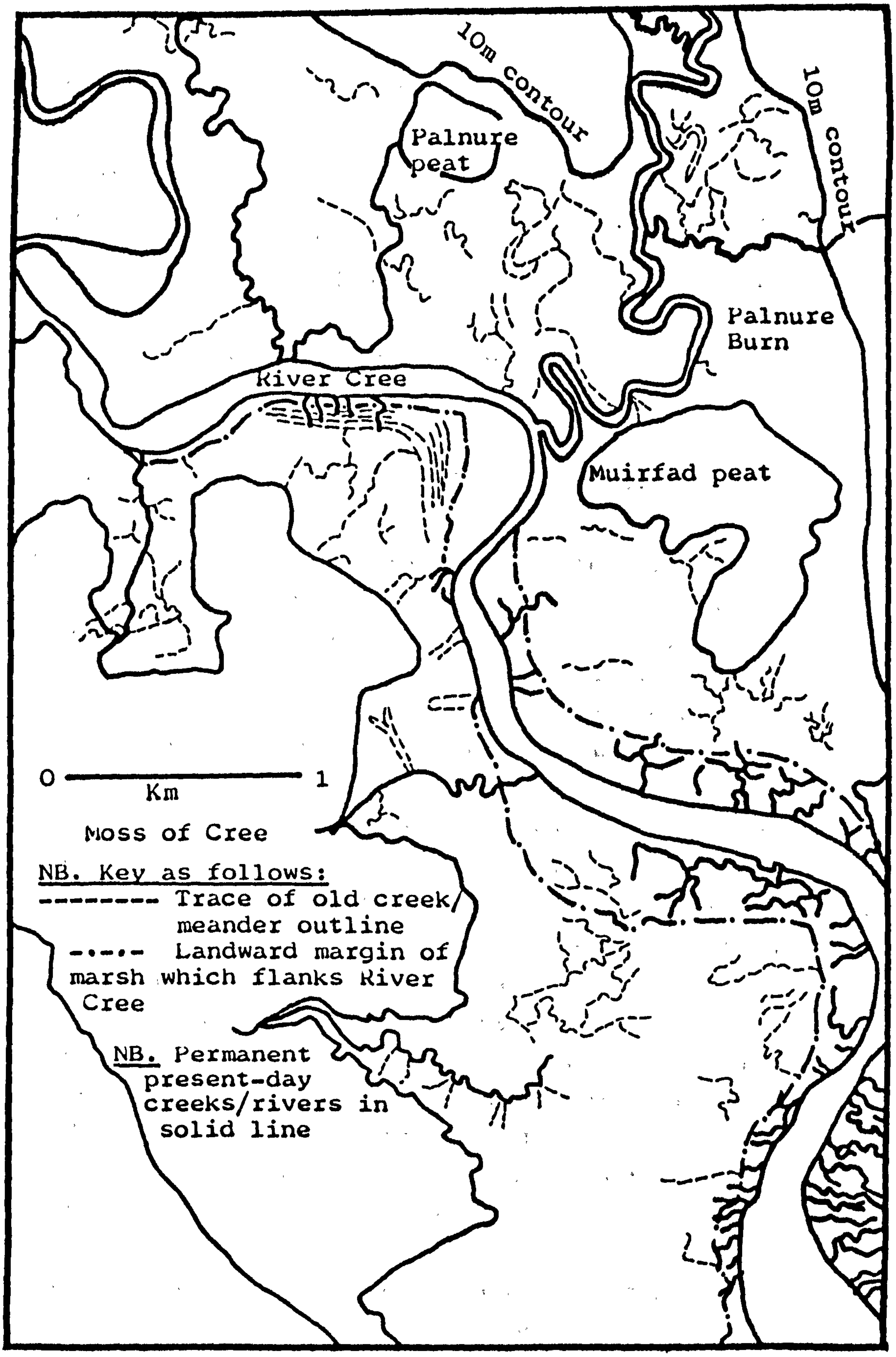


Fig.3.3 "Ancient" meander scars and tidal-creeks of the River Cree and Palnure Burn

6. Meandering tidal-creeks and associated channel-margin slumps and point-bar front slumps

Well-preserved examples of Holocene slumping allow a direct comparison with present-day equivalents (see Table 3.4).

Tidal-creeks of varying size are recognisable at present. Tidal-creeks also varied in size in the past. Small-scale Holocene creeks situated on older intertidal flats are recorded on aerial photographs.

Small-scale sedimentary structures and biological features

A major problem in comparing present-day sedimentary structures and biological features (samples taken by box coring method and preserved by peels; see Chapter 10.1.3) with those of the past, is that of difference in size-grade of the sediments being compared. The present-day sedimentary structures are found in coarse-silt to coarse-sand grades, the majority being in fine sand. They are very predictable in their spatial distribution as they typify the environment in which they are found. This would also be expected to be so in the Holocene deposits. In fact, only a few examples of present-day features can be related directly to ancient features (e.g. herringbone cross stratification, tidal bedding). The distinct lack of well-preserved sedimentary structures in the older deposits is due to the fact that there has been a coarsening in the grade of material deposited, from chiefly silts and muds during early- to mid-Holocene times to a sandier grade at the present-day. As the estuary filled in and matured, the grade of material deposited coarsened.

The lack of evidence of burrowing in the Holocene deposits is also considered to be a function of grain size. It is possible that the dark grey-blue clays discussed in Chapter 5 had too high a water content, and were not cohesive enough,

Present-day slump examples	Type of slumping	Early to mid Holocene equivalent examples
Meikle Carse, bank of River Cree locations NX 4442 6267 to NX 4473 6264 Bank of Palnure Burn at Muirfad meander	Rotational channel margin or flank Rotational channel margin and point-bar flank	Muirfad meander section NX 4541 6281 to NX 4554 6277, Long Loop section NX 4523 6244 to NX 4524 6238
Carsenestock point-bar flank c. NX 4408 6249 (noted after period of foul weather) Moneypool Burn point-bar flank c. NX 4670 5858	Rotational shear failure, toppling of debris, plastic deformation Rotational shear failure and high degree of plastic deformation	Blackstrand, Meikle Carse section NX 4409 6270 to NX 4417 6268, point-bar flank East end of Meikle Carse section NX 4493 6257, point-bar flank

Table 3.4 Past and present rotational slides and slumps in the upper Cree estuary and Palnure Burn areas NB Scale of the above features varies considerably but is not considered a viable criterion when classifying

for burrowing. There appears to be no evidence of burrowing in the older pale grey clays. Possibly this substrate was too hard for burrowing, but more probably it was not a suitable infaunal environment for other reasons. The only biogenic material that is encountered in the dark grey-blue clay unit is found in the gravels interbedded within the clay, and that material consists of transported shell debris.

Most faunal material included in the Holocene deposits appears to be derived from nearby estuarine or marine areas, only a small proportion occurring in or near to life position. This indicates highly active reworking of estuarine flats and older flanking deposits by lateral migration of the River Cree and its tributaries. Therefore, it is highly probable that because of the high energy of the environment there is a lack of infaunal material. Nothing could live there due both to constant erosion and to deposition of muddy sediments. The same claim seems to hold true for the upper Cree estuary at present in the vicinity of Meikle Carse since virtually no burrowing is observed. There are a few traces of <u>Corophium volutator</u> but the burrows of this amphipod are hardly likely to be preserved in older deposits.

On first consideration, the high energy of the environment of deposition appears to conflict with low energy deposition from suspension on the muddy intertidal flats. The apparent paradox, however, is explained by the fact that deposition occurred in a restricted embayment (Wattenschlick type). Therefore, once trapped at the head of the estuary, sediment could not be moved seawards easily.

3.2.2 The lower Cree estuary

The lower Cree estuary, south of Creetown, can be divided into two environmentally-distinct areas, now discussed.

<u>Creetown to the estuary mouth</u>

The channel of the River Cree divides south of Creetown, with the development of intervening elongate intertidal banks.

There are also extensive marginal intertidal mudflats (vegetated and unvegetated) on the western margin between NX 4650 5810 and Wigtown (NX 4360 5550). The estuary is being infilled from the west by easterly progradation of these intertidal flats. The eastern side of the River Cree is flanked by narrow mud-and-gravel estuarine beaches.

Between Carsluith and the estuary mouth, the estuary is considered to be a tidal inlet. A marine coastal morphology - e.g. estuarine beaches and a rocky, cliffed shoreline - is developed. The western bank of the Cree estuary is flanked by extensive tidal flats (Baldoon Sands) extending from Wigtown to Jultock Point (NX 4880 4900).

Present-day environments: lithofacies, sedimentary features and dynamic energy

1. Intertidal shoals and banks

These are broad, flat, or very gently seaward-sloping areas of sandy mud and fine to medium sand.

2. Intertidal mudflats

These consist of broad expanses of seaward-sloping areas of muddy sand to sandy mud. The mudflats are vegetated at their western (landward) margin. They are dissected perpendicular to the main flood/ebb direction by a dendritic pattern of numerous creeks. Sediments coarsen in grade towards the channels. Major processes that are active include deposition from suspension as the flood water flows over the flats in a sheet-like fashion.

3. Tidal Inlet

The tidal inlet consists of linear tidal and subtidal sand ridges, positioned parallel to the main tidal currents. Sediment is of coarse sand grade.

4. Estuarine beaches

These consist of patchy, narrow developments of sandy silts and fine sand deposits, located at the estuary margin, e.g. at Carsluith. Concentration of coarser-grained sediment, such as gravels, is found at the landward margin of the beaches, near H.W.M.S.T. Beaches become progressively sandier in a seawards direction.

Dynamic environment

The dynamic environment is dominated by tidal currents that initiate ebb/flood avoidance patterns and interact seawards with waves.

Early- to mid-Holocene equivalents of present-day environments in the lower Cree estuary

1. Intertidal mudflats

Extensive intertidal mudflats characteristic of the western flank of the estuary, and extending from location NX 4650 5810 to Jultock Point, are probably similar to the wide expanses of laterally-accreting mudflat of the Meikle Carse section at the head of the Cree estuary.

2. Estuarine beaches

Estuarine beaches similar to those of the present-day lower Cree estuary were better developed than at present between Creetown and Carsluith in late-Holocene times. Beach deposits accumulated above intertidal flats by coalescence of shoreward-migrating bars (Chapter 7.5). Additional features that are not present in the estuary today (i.e. a spit and ridges) were also identified.

CHAPTER 4 - METHODS OF INVESTIGATION

The field and laboratory methods listed in Table 4.1, and described below, were utilised to record and collect the necessary data for further analyses.

4.1 FIELD METHODS

4.1.1 Sedimentary logging and instrumental levelling

Lithological changes, sedimentary structures and organic features were recorded by the logging of vertical profiles (Fig. 4.1). Usually, these profiles were located along an incised river bank at random intervals, of less than 10m. Inter-profile distances of more than 10m commonly were interrupted by c. 7 to 10m wide (occasionally up to 20m+), slumped-bank sections, which disrupted the sequence and rendered it unsuitable for recording. Each log was measured and recorded downwards from an arbitrary "zero recording point" at a measured altitude, above (or below) Ordnance Datum, determined by instrumental levelling of the profiles to an established Ordnance Survey bench-mark. This allowed precise inter-log and inter-section correlation to known altitudes A.O.D./B.O.D. The average depth of a log profile was c. 3 to 4m. To enable a continuous vertical profile to be constructed, a series of steps was dug down the channel bank (Fig. 4.1). Features and depth of the step face were then noted. A total of 41 profiles was recorded using this method.

4.1.2 Sample collection

Representative samples of all lithologies encountered were taken at random levels, and labelled with the name of the section location, log and specimen number. For example, MC A sp8, denotes sample 8 of log A, Meikle Carse section. The position of the sample relative to O.D. was also noted.

4.1.3 Mapping

In addition to the examination of exposed bank sections, the

Field Methods	Laboratory Methods
Sedimentary logging and instrumental levelling	Sample preparation and analysis
Sample collection	Correlation and interpretation of supplied borehole data
Mapping	Study of aerial photographs

Table 4.1 Summary of methods of investigation

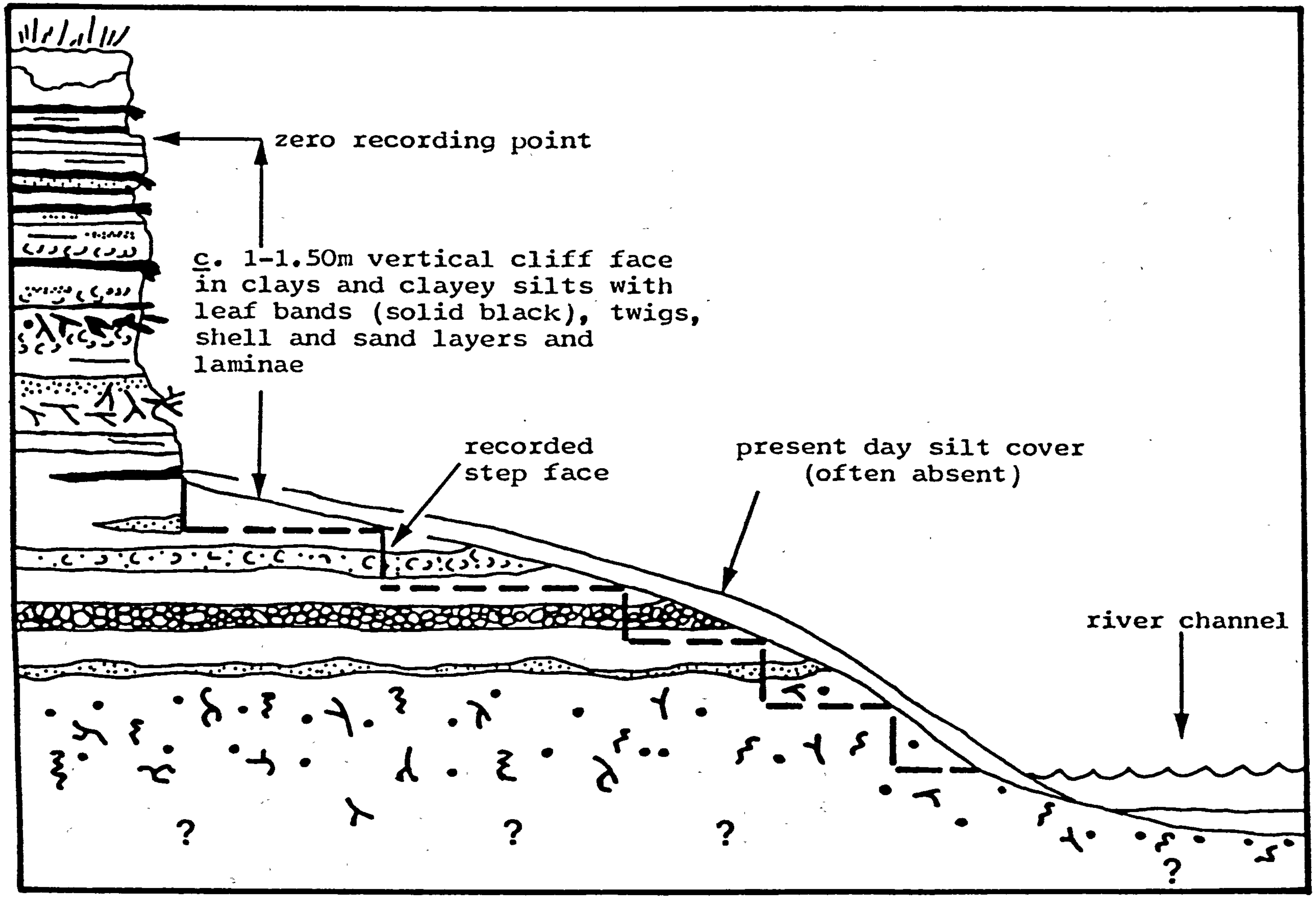


Fig.4.1 Section through incised bank margin to show method of construction of vertical log profile

study area was mapped at the scale of 1:10,000 on Ordnance Survey maps. Mapping involved the delineation of prominent geomorphological (surface) features and their boundaries by recording slope changes, for example the remnant coastal cliff, extent of fluvio-glacial terraces and areas of raised peat, with the aim of establishing precisely the limits of the Holocene marine transgression.

4.2 LABORATORY METHODS

4.2.1 Sample preparation and analysis

Samples of all representative lithologies were obtained with the aim of qualitatively determining the vegetable matter (i.e. leaves, nuts, twigs, grasses), and the macro- and micro-faunal content to establish evidence for the environment of deposition of the sediment. Grain attributes (i.e. shape, roundness, sphericity, sorting and texture) of the inorganic component were also noted. Bearing these objectives in mind, the following sample preparations were undertaken.

Sieving method (for all samples)

A profile and its samples were selected. Each sample was halved, one half being retained for future use if necessary. The halves to be treated were placed in beakers, labelled with the position of the sample A.O.D./B.O.D., dried and weighed. They were then soaked for one to two days in hot water which contained washing-up detergent. The samples were periodically agitated with a glass rod to facilitate dissolution of the clay or sandy material. The samples were then passed through a stack of sieves in the following decreasing order of mesh sizes: 2mm, 1000μm, 500μm, 250μm and 75μm. All material finer than 75μm i.e. clay, silt and some very fine sand, was lost. The majority of the microfossils were retained on the 250μm and 500μm sieves. Each fraction was gently washed into an evaporating dish and dried at 80°C. Finally, the fractions were weighed prior to bottling. By weighing the sample prior to sieving and weighing the individual fractions after sieving and drying, it was possible to calculate the amount of clay and silt lost and hence estimate the percentage of clay and silt in each sample. It must be noted that the initial weights of the individual samples varied greatly.

4.2.2. Supplied borehole data

Borehole data and samples collected by Dr. W.G. Jardine in 1970, but not analysed then, were obtained for the Parkmaclurg borehole (see Chapter 5.1.1/5.2.1) and the Cassencarie boreholes (see Chapter 7.4). In the course of this study, access to useful borehole information was also gained via contacts established with several civil engineering consultant companies. The borehole information was acquired in relation to both major and minor road schemes (Table 4.2), now completed or still in progress, within the study area.

4.2.3 Aerial photography

The study of aerial photographs (at various scales), of the Cree estuary from 1946 to the present day has revealed information vital to the reconstruction of palaeoenvironments. Upon close examination, the positions of tidal creeks and gullies of a former tidal-flat, and the positions of now-abandoned and infilled meanders of the Palnure Burn can be established. Additionally, the pattern of lateral migration of large-scale channels and creeks can be traced, and rates of erosion and deposition estimated.

Major and minor road schemes completed (C) or still in progress (P) within the study area		Number of boreholes/ trial pits which supplied useful information
1. Newton Stewart (A75) By-pass (Scottish Development Department)	(C)	1
2. A75 Improvement, Palnure (Thorburn & Partners)	(C)	6
3. Creetown (A75) By-pass (Jamieson McKay & Partners)	(P)	34
4. Carsluith (A75) By-pass (Thorburn & Partners)	(C)	35
5. Gatehouse-of-Fleet (A75) By-pass (Babtie Shaw & Morton)	(C)	19

Table 4.2 List of major and minor road schemes providing geological information used in the thesis. Names in brackets are those of the civil engineering consultant companies responsible for the schemes

PART A

STRATIGRAPHY, SEDIMENTOLOGY AND PALAEOENVIRONMENTS OF HOLOCENE COASTAL DEPOSITS

CHAPTER 5 - THE UPPER CREE ESTUARY AND PALNURE BURN SECTIONS

5.1 DESCRIPTION OF THE LOGGED SECTIONS AND BOREHOLES

General Introduction

Chapter 5.1 comprises the systematic description of logged sections and boreholes in the upper Cree estuary, in a west to east direction and in the order that the sections were completed during the course of fieldwork.

A general (summary) stratigraphical column and map showing locations of all sections described in the chapter is presented in Fig. 5.1. The latter should be consulted frequently in conjunction with the text.

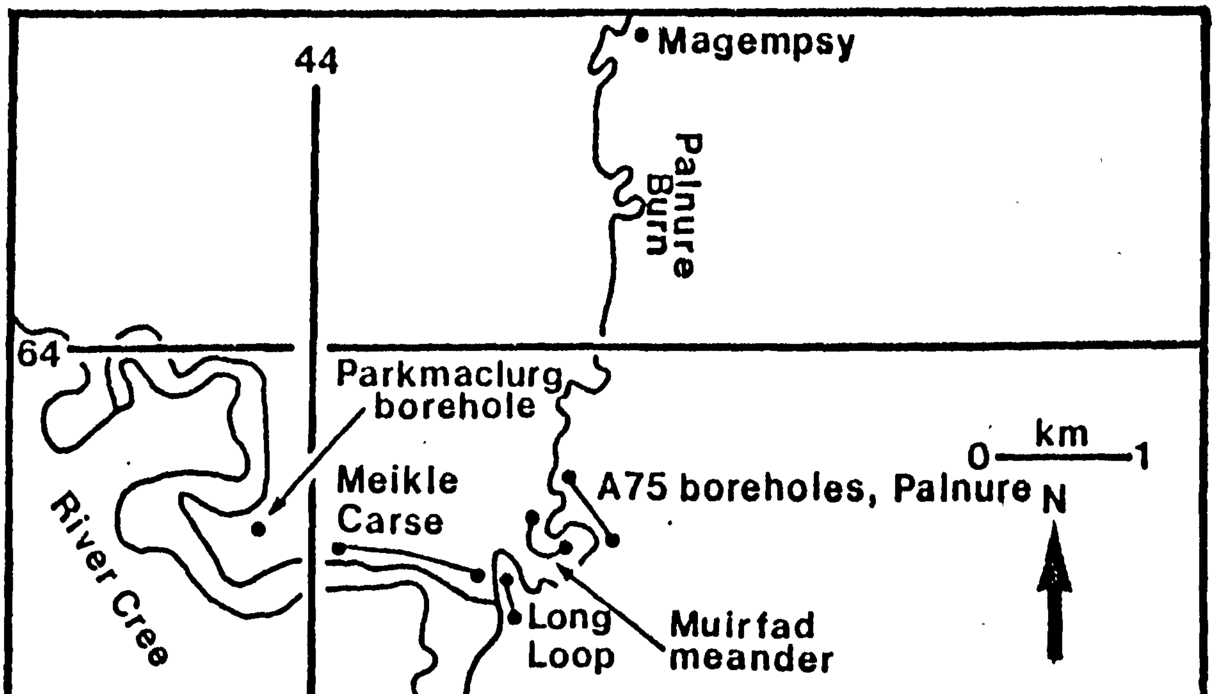
Individual logs are denoted by letters of the alphabet. The alphabet is used to distinguish logs on both the Palnure Burn and River Cree sections. The logs of the latter bear the prefix letters "MC", indicating their location on the Meikle Carse section. "PMCBH" in the sample description (Chapter 5.2.1) indicates samples taken from the Parkmaclurg borehole.

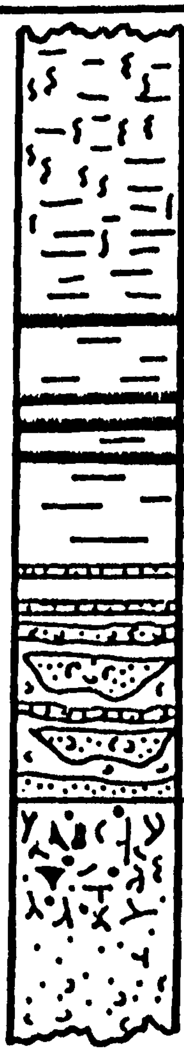
In certain sections it is difficult to describe characteristics of the sediment without making inferences regarding, or implying what were, the environmental conditions of deposition. This approach is kept to a minimum. Most of the environmental interpretation is considered in Chapter 5.2. Description of the section and inferences concerning environmental conditions are given together where it is thought that the environmental inferences enhance the description.

5.1.1. River Cree: Parkmaclurg borehole

5.1.1.1 Introduction

The Parkmaclurg borehole (Appendix p.322), is situated at NX 4356 6291, south of Parkmaclurg Farm at a ground





Lithology	Environment
Very finely laminated sands, silts and clays penetrated by oxidised root channels	Very high tidal-flat/marsh. NB. Upper 2m of tidal-flat consists of dried-out crust
Dark grey-blue clays with fine sand/silt alternations. Abundant twig remains and leaf layers	Upper tidal-flat, horizontally bedded and prone to slumping and rotational sliding into flanking channels
Dark grey-blue clays interbedded with fining-upward coarse to fine sands, shell pavements, lags & gravels	Lower tidal-flat, point-bars cut by shallow, tidal channels and flanked by shell/gravel pavements
d/c	
Pale grey clays rich in organic matter. Clays occasionally pink-grey colour. Minor amounts of sand & shell debris	Varies from "marine" estuarine at depth to upper tidal-flat/boggy marsh at the top of the pale grey clays

Fig.5.1 Summary stratigraphic column and map showing location of sections described and discussed in Chapter 5. d/c - disconformity

altitude of 9.20m A.O.D., Fig. 5.1a). The borehole was sunk over a period of four days and reached 3.20m B.O.D., at a depth of 12.40m below ground level. Casing extended to 0.20m B.O.D., 9.40m below ground level. Eight samples of clay were collected as drilling proceeded, all but one being disturbed when retrieved. Two different lithologies were recorded in the borehole. These are described below from the base of the borehole upwards.

5.1.1.2 Description

<u>Pink-grey clays (3.20m B.O.D. to 4.95m A.O.D.)</u>

8.15m of pink-grey clay were recorded in the borehole. The clay, exhibiting patchy and faint laminations of fine sand, is very stiff in consistency. It also contains black decayed vegetational matter and small twigs.

<u>Grey clays (4.95m A.O.D. to 9.20m A.O.D.)</u>

At 4.95m A.O.D., the stiff pink-grey clays are overlain unconformably by 4.25m of darker grey and grey-brown clays that exhibit a sticky or plastic texture. At <u>c</u>. 6m A.O.D., the grey clays have horizontal leaf/clay alternations. The brown coloration of the clays in the top 2m of the borehole is due to its drier, oxidised, weathered nature.

5.1.2 River Cree: Meikle Carse section

5.1.2.1 Introduction

The Meikle Carse section, trending from W to E and comprising 26 log profiles (Appendix p.323-336), is situated on the outer bank of the River Cree between locations NX 4409 6270 and NX 4493 6257, SW of Meikle Carse (now re-named Coopon) Farm (Fig. 5.2).

In the following description, the section is divided into three parts, as it was recorded in the field. Interpretation is dealt with similarly in Chapter 5.2.2. A general conclusive summary for the Meikle Carse section follows separately.

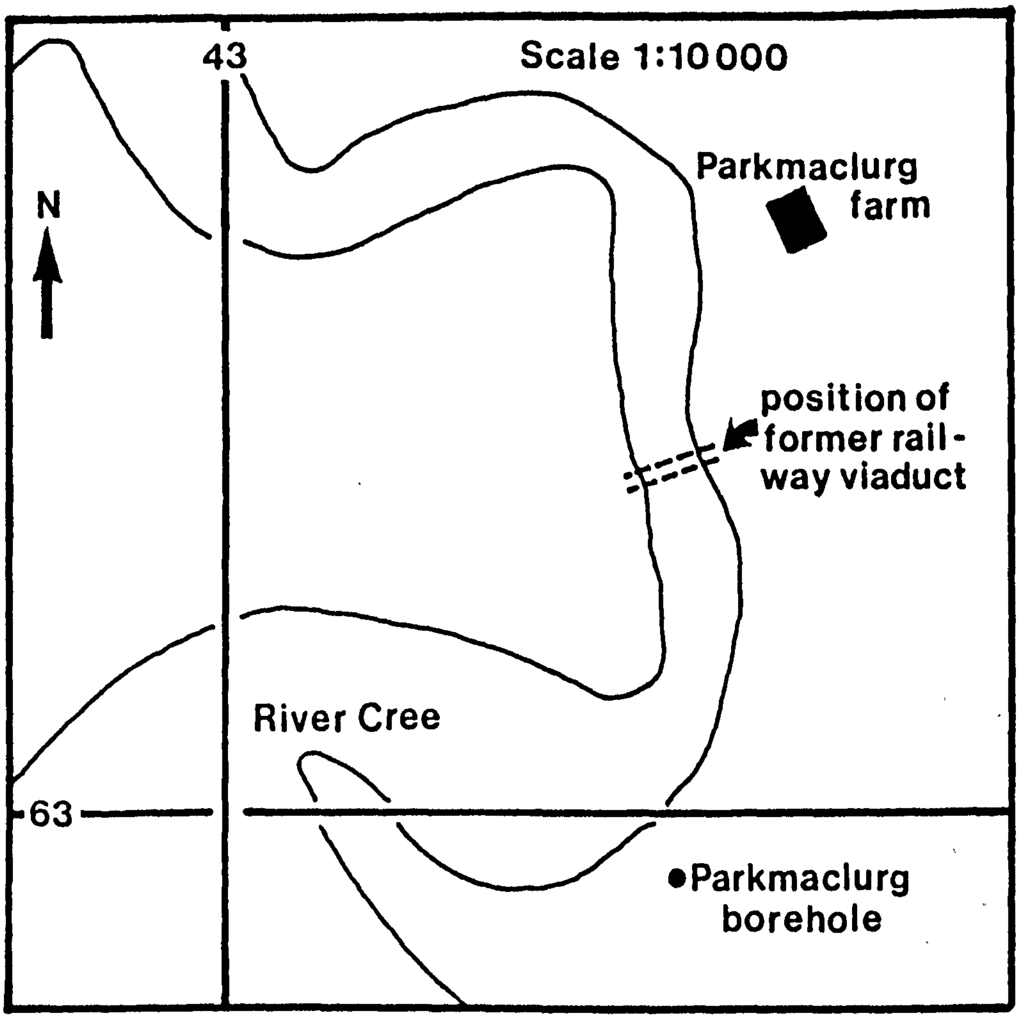


Fig.5.1a Map to show location of Parkmaclurg borehole, River Cree

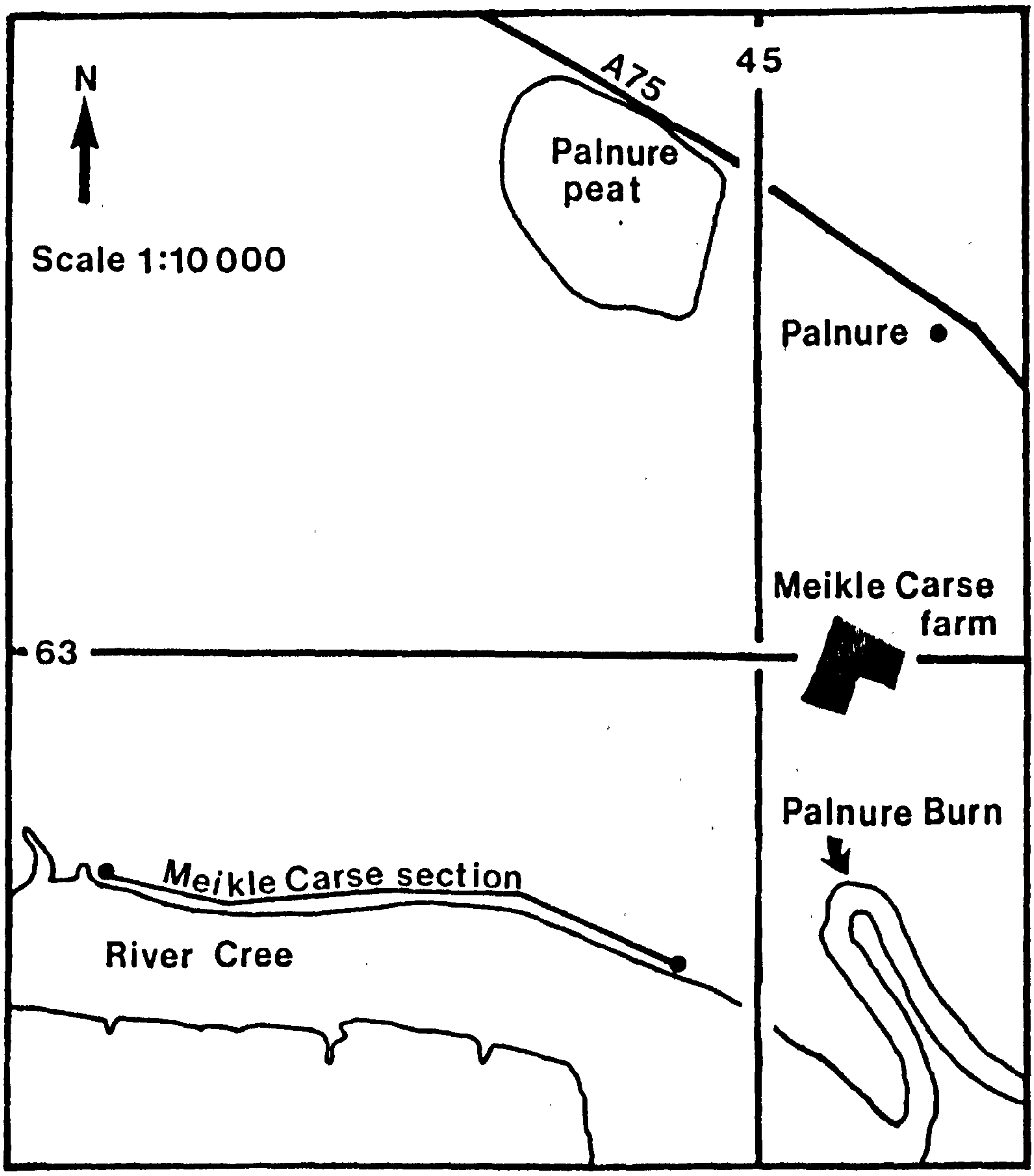


Fig.5.2 Map to show location of Meikle Carse section, River Cree

West to east, the Meikle Carse section comprises Logs V to Z (Fig. 5.6, p. 68), A to M (Fig. 5.16, p. 108) and N to U (Fig. 5.18, p. 123).

5.1.2.2 Description

A. Meikle Carse section: Logs A to M (locations NX 4432 6265 to NX 4450 6266) - see also Fig.5.16, p.108

Pale grey clays

The pale grey clay is the lowest logged unit. Its boundary with the overlying dark grey-blue clay is undulatory along the 200m section. The junction is also unconformable and marked by an erosion surface. The contact between the lithological units is either abrupt and planar or abrupt and exhibiting small-scale irregular relief, with an intervening coarse sand and shell lag deposit forming impersistent lenses or pockets. The base of the pale grey clay was not recorded. The clay has a consistent silvery grey coloration throughout the section. Its most characteristic feature, apart from its distinct colour, is its malleability; it is very stiff, and is easily moulded to retain its shape. This is due to the very low water content, rendering it cohesive and compact. The organic content of the clay is very high, consisting of sooty, carbonaceous spots and streaks with no preferred orientation. There is no evidence of bedding, i.e. the clay appears to be structureless or massive.

Dark grey-blue clays

The above clays form the main constituent of the logged profiles, resting disconformably on the pale grey clays. The sequence is horizontally bedded clays alternating with ferruginous fine to coarse gravel units in the lower portions of the logged profiles. These coarser-grained units (pebbly in places) are discussed separately on page 56, together with the finer sand fractions found at higher levels in the logs. The clays, a dark grey-blue colour when fresh, weather to a pale grey and develop a blocky fracture. When fresh the clays can be termed "plastic" due to the high water content. They are too fluid to be moulded like the underlying pale grey clay.

Organic features within the clays comprise frequent carbonaceous streaks and patches in the top 1 to 1.50m of the logged profiles. The "patches" have a bright blue nodular core of the earthy and powdery mineral vivianite. This is a hydrated ferrous iron phosphate, colourless when fresh, but changing to its characteristic bright blue or turquoise colour as a result of oxidation. It is a secondary mineral, frequently found in clays, and in association with organic remains.

Shelly macrofauna, although occasionally randomly scattered through the clay, is usually restricted to bedding plane surfaces, or is associated with the coarser sand and gravel units. No bioturbation is encountered within the clays.

Characteristics of the interbedded sand and gravel deposits

The grade of material, classified on the Udden-Wentworth scale, varies from very fine sand to pebbles and is distributed from top to base throughout the logged profiles as follows:-

(a) Very fine to fine pale yellow sand, located within the top 1 to 1.50m of the logs. The bands do not exceed 0.005m in thickness usually occurring as thin laminae.

(b) Fine to coarse sand and gravel.

Fine to medium grade sand occurs as 0.02 to 0.03m thick impersistent horizontal bands, lenses and pockets within the dark grey-blue clays. The coarser-grade bands are thicker, averaging 0.04 to 0.06m in thickness, but occasionally occurring as wedges, up to 0.50m in the basal parts of the logs. These are considered to be channel-floor infill deposits. Very coarse sand and gravel-grade material forms laterally-persistent sheets, correlatable from log profile to log profile. Westwards of Log E, the sheets thicken and exhibit the characteristics of channel-floor and infill deposits. This development of channel units is further discussed in Chapter 5.2.2.1.

The majority of sand-grade bands appear to be small-scale cut-and-fill units, having sharp contacts with the overlying and underlying clay. Most of the lower contacts are erosive. The relief is highly irregular (Fig. 5.3). It is suggested that the clay (A) has been subject to sharp, plucking action, being "sucked" out in chunks under high energy (? storm) conditions. The sand is then deposited in the hollowed out surface. The sharp, upper contact of the sand with the clay at B marks the return to deposition of clay from suspension under relatively lower energy conditions. It is possible that the aforementioned process operates under storm conditions or as part of a "sucking" action set up under excessive flood/ebb tidal conditions.

The coarse sand to gravel sheets are also believed to represent large-scale cut-and-fill units, of a very broad palaeo-River Cree. The gravels are semi-consolidated and highly ferruginous, banded by iron but not bedded internally. The percolation of iron-enriched water through the gravels is responsible for cementation of the grains and clasts, leading to their consolidation and compaction which is initiated by the overburden of clays.

<u>Characteristics of the organic (vegetational) component of the dark grey-blue clays</u>

The total vegetational component of the logged profiles is great, the top 1 to 1.50m consisting of horizontally-layered clay and leaf intercalations. The organic layers may be further distinguished into five types of occurrence according to size of fragments.

1. Filamentous laminations: disseminated leaf fragments.
2. Layers, averaging 0.02 - 0.03m in thickness, consisting solely of leaves.

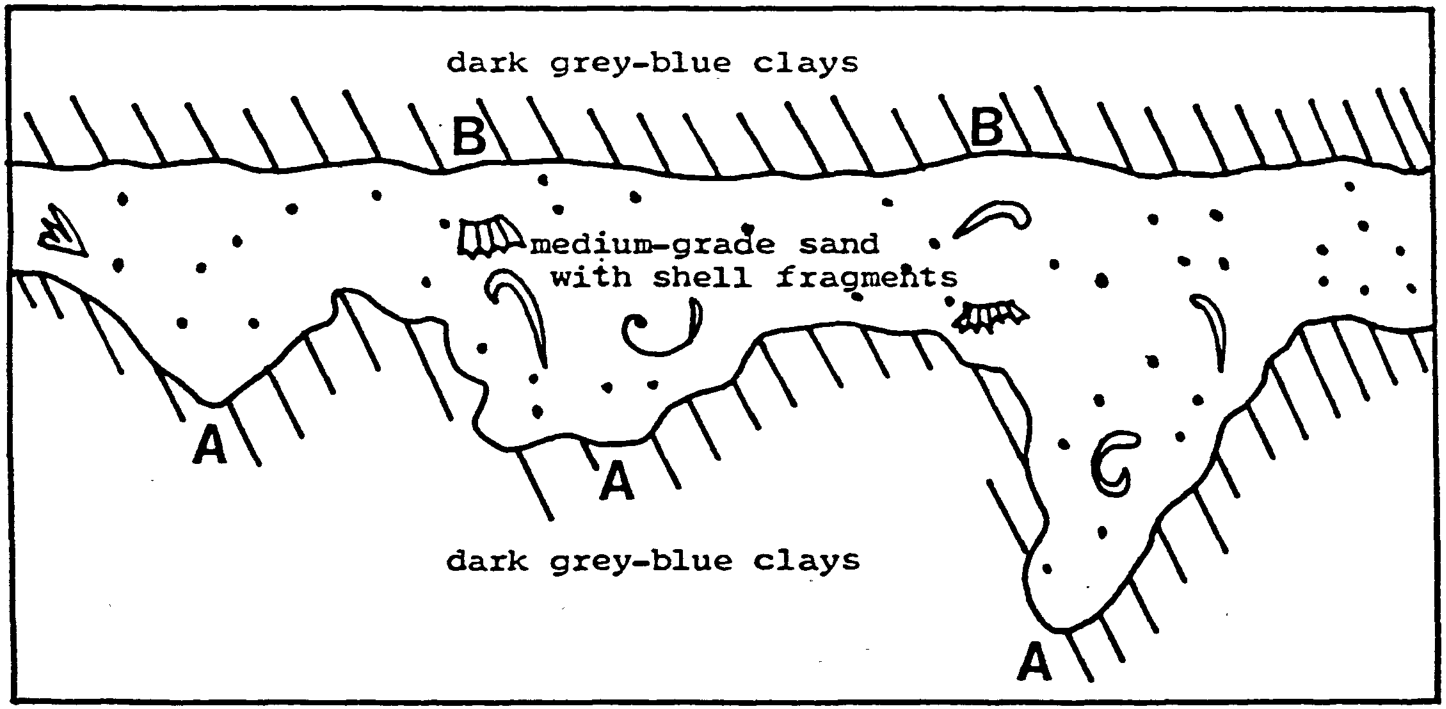


Fig.5.3 Sketch to show contacts of sand bands within the dark grey-blue clays. NB Highly irregular relief along erosion surface A, sharp, even contact with the overlying clay along B. Sand band c. 0.005 to 0.01m in thickness

3. Leaf layers in association with nuts, twigs and woody debris - the latter frequently oriented.

4. Carbonaceous streaks, spots and smudges.

5. Branch and tree-trunk remains, occasionally oriented.

Typical clay/organic intercalations (categories 1 and 2) exhibit a "pinch and swell" of the banding (Fig. 5.4), which may be due to slight differences in compaction of the clay. The leaf layers are laterally extensive or continuous suggesting that they were deposited in a quiet, low energy environment. The majority of leaves have been identified as those of Betula (birch). The leaf bands are regular and their abundance and intactness suggests continuous derivation from a nearby source of dense vegetation, followed by a short period of transportation. It is possible that the leaf layers are almost in situ. Commonly, the twig and hazelnut (Corylus) concentrations show no preferred orientation, except when they occur as channel-lag deposits within cut-and-fill units. Tree trunks and boughs are found singly and forming log "jams" at the base of the sequence. Individual trunks are oriented. Their orientation and its significance are discussed in Chapter 5.2.2.1. X

Generally, there is an increase in the proportion of organic layers towards the top of the logged profiles, corresponding with a decrease in proportion and eventual absence of shell and sand bands. Down-log the situation is reversed. In the lower gravel and dark grey-blue clay units the macro-organic content is confined to large scale washed-in tree-trunks and branches, together with finer woody debris.

B. Meikle Carse section: Logs N to U (locations NX 4490 6260 to NX 4474 6265)

The section trends W to E, from Log T to Log R (Fig. 5.5, locations NX 4468 6266 to NX 4493 6257) and consists of

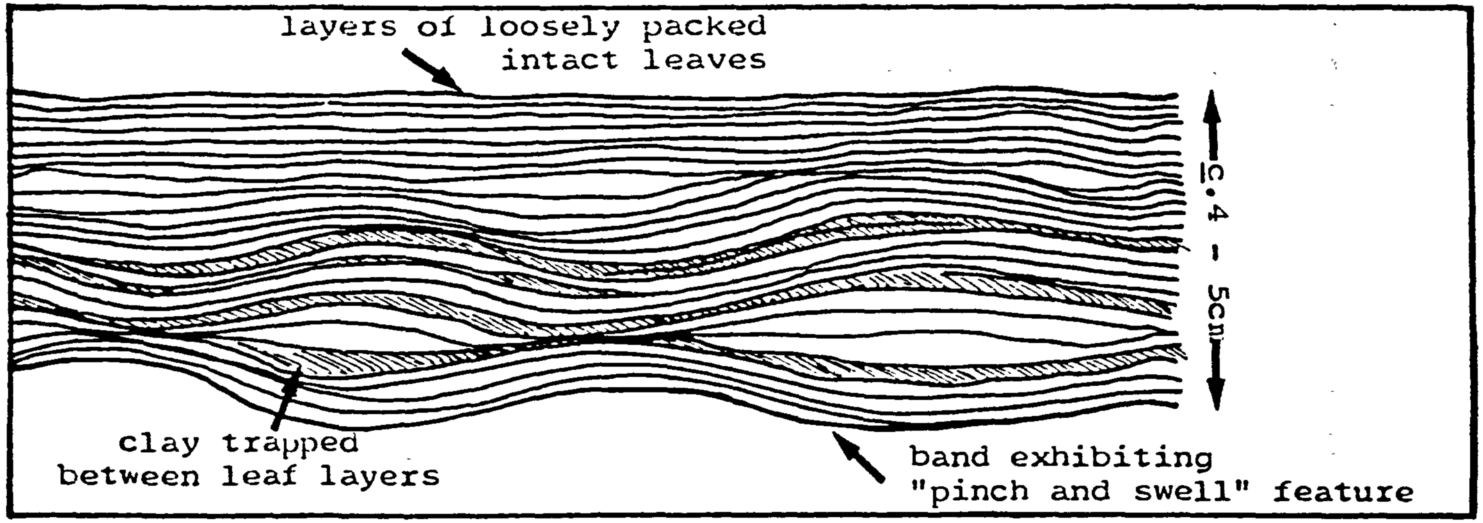


Fig.5.4 Sketch to show "pinch and swell" nature of organic banding

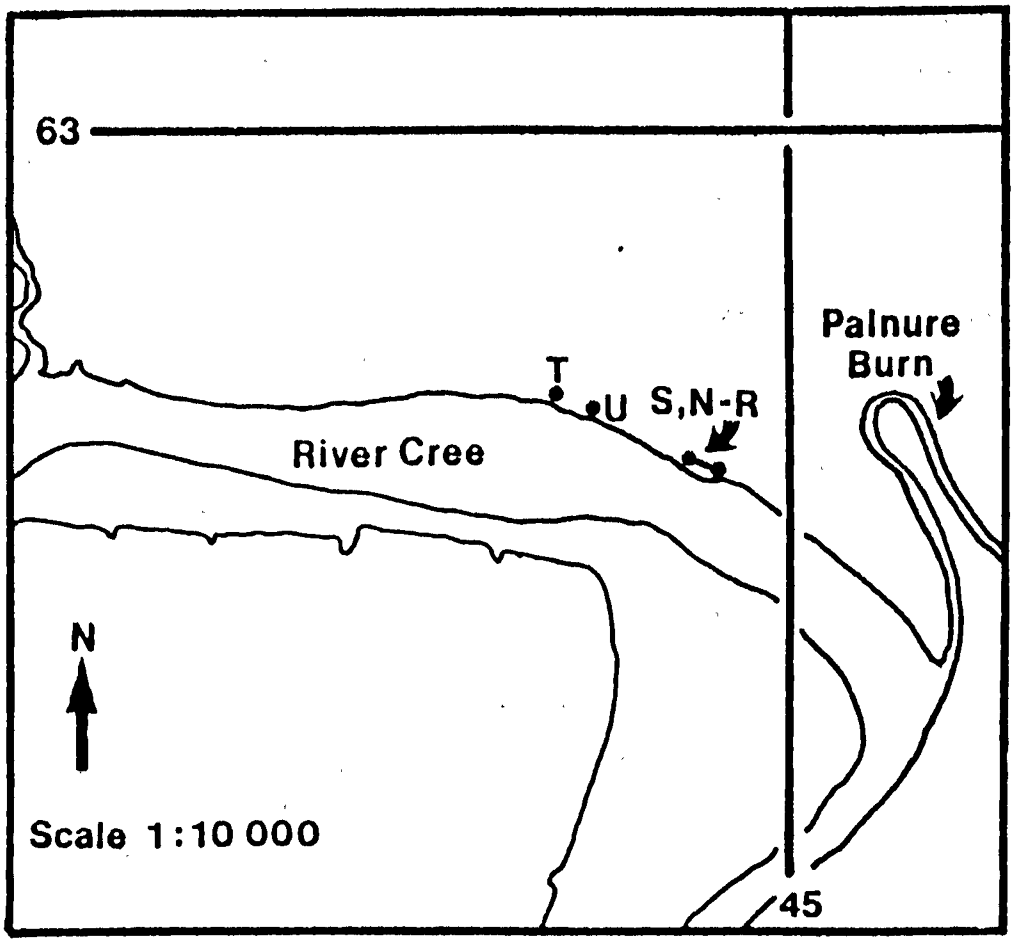


Fig.5.5 Map to show location of Meikle Carse section, logs N to U, River Cree

eight logged profiles (Fig. 5.18, p.123 and Appendix p.330 - 333).

Three major lithostratigraphical units were recognised, based upon their vertical and lateral relationships, now considered. At no point along the length of the section was the contact with the (presumed) underlying pale grey clays recorded.

Dark grey-blue clays - Lithostratigraphic unit 1 (inferentially lower tidal-flat, channel-floor environment)

Typical dark grey-blue clays, interbedded with fining-upward and gently-dipping-eastward storm gravel and shell units are evident at the base of MC T, U and S, and are thickest at U (1.55m). The grade of the gravel deposits coarsens laterally eastwards from fine in MC T, through MC U where it is medium to coarse, reaching cobble grade in MC S. The cobbles are sub- to well-rounded. A thin (0.03m in thickness) band of coarse gravel and shells is also present at the base of MC N. The lateral coarsening may indicate the onset of channel conditions in an E direction. The unit lies at c. 0m O.D. to 1.60 - 1.75m A.O.D., its boundary with lithostratigraphic unit 1a dipping gently eastwards. Beyond MC S at c. 0m O.D. to 3m A.O.D. (i.e. in MC N, P, Q and R), the dark grey-blue clays pass laterally into a pale to mid-grey micaceous silt (lithostratigraphic unit 1b, described page 65). The relationship between the dark grey-blue clays of unit 1 and 1b is not clear, but the latter may represent contemporaneously-deposited channel-infill sediment (see discussion, page 125).

Dark grey-blue clays - Lithostratigraphic unit 1a (inferentially prograding upper tidal-flats/slump)

This unit is present in all logs except MC R. It varies from 1.85m in thickness in MC T to c. 2m in MC U and occurs between c. 1.60 to 1.75m A.O.D. (the boundary with unit 1) and c. 3.60m A.O.D. The unit consists of horizontal alternations of dark grey-blue clay and leaf bands in the section west of MC U. Eastwards of MC U, the dip of these strata becomes progressively steeper in an E to SE direction, ranging from 9° to c. 35°+. The beds are at their steepest in MC S where they also are faulted. Eastwards of MC S as far as MC Q, there is a zone of warped and folded leaf and clay alternations that appear to represent a slump, which probably resulted from failure of the oversteepened beds. Such a situation would commonly occur on the progradational margin of a migrating intertidal bank or point-bar flanking a channel (see discussion Chapter 5.2.2.1, p.125). The dark grey-blue clays of unit 1a merge laterally with micaceous silt (unit 1b), thought to have originated in a channel (see MC P and Q).

Sedimentary characteristics of the disturbed zone between MC S and Q are now considered. The slumped portion of the sequence in MC S is 1.50m in thickness and unconformably overlies sediments that are regarded as lower tidal-flat deposits, together with 0.50m of grey micaceous silt (representing channel-infill material). The slumped sediments in turn are overlain by very high tidal-flats of unit 2, consisting of grey-blue clay containing irregular and discontinuous laminae of buff coloured silt to fine sand, c. 3 to 4mm in thickness. Also present are abundant warped and gently-folded leaf bands. The base of the disturbed zone is faulted at its contact with underlying channel-infill (in this case marginal) deposits (unit 1b). Leaf bands are displaced. A tree trunk, possibly stranded at the channel margin, is also present at this level.

The thickest preservation of disturbed deposits is present in MC N; the sequence is 2.20m thick, resting on mid-grey micaceous silt of unit 1b and overlain unconformably by reworked upper tidal-flat deposits of unit 2a (see description, page 65). The deposits are of dark grey-blue clay and leaf band alternations which are extensively warped, gently folded with a general indication of E to SE movement. The dark grey-blue clay becomes progressively greyer, micaceous and coarser (to silt grade) in the top 1m of the disturbed unit. Additionally, the topmost 0.40m contains impersistent laminae of clay and very fine sand. Numerous vertical "root channels" are present within the top 0.80m of the disturbed unit. It is likely that colonisation by vegetation (probably reeds) occurred after slumping since the roots are vertical and exhibit a crosscutting (discordant) relationship with the warped deposits. Furthermore, the vegetation probably helped stabilise the slumped sediment pocket.

The slump is 0.67m thick in MC O and is composed of pale grey-blue micaceous clayey silt which exhibits very fine sand laminae. The clayey silt alternates with warped leaf layers. Vertical indurated root-channels similar to those of the previous log, MC N, are recorded as being occasional.

A thin disturbed zone with apparently NW-dipping leaf bands is present in MC P and Q, probably due to the fact that most of the slump had been eroded along its outer margin, i.e. the portion resting in the channel being most susceptible to destruction by erosion.

In MC P, a thin intercalation of clay and leaves is underlain by pale grey micaceous silt of channel-infill origin and is overlain unconformably by reworked high tidal-flat deposits. At MC Q a thin development of steeply-dipping (to the NW) silt-and-leaf-band alternations erosively downcut into and are overlain unconformably by unit 3, the intervening unit 2a having been overlapped and pinched out. It is possible that the aforementioned NW-oriented leaf bands could be discrete, disoriented blocks.

Pale grey micaceous silts - Lithostratigraphic unit 1b (inferentially channel-infill deposits)

The silts or silty clays are present eastwards from MC S to

MC R, where they are best developed. Their colour varies from dark grey in MC S to mid grey in MC P, and pale to silvery grey in MC Q and R. They are consistently highly micaceous and structureless but contain finely fragmented shell material between 0.865m and 1.865m A.O.D. in MC R. The relationship between unit 1b and 1a is uncertain. These units may be lateral equivalents with a gradational change (variation in sediment colour seems to suggest this).

Brownish-grey clay with root channels - Lithostratigraphic unit 2 (inferentially very high tidal-flats)

This unit was recorded in MC S only, present at between 3.570m and 4.570m A.O.D. and consisting of horizontally-bedded alternations of brownish-grey clay and buff coloured silt to fine sand bands (forming couplets). Individual clay bands average 0.01 to 0.05m in thickness, whilst the silt/fine sand bands are c. 0.01m in thickness. The horizontal bedding is cut by vertical root channels, which are abundant. They are minimal in their disturbance of bands and laminae. The vertical channels are indurated, exhibiting oxidised margins c. 0.005m in width on either side of the channels, developed in situ as a result of oxidation of the sediment around the root. The oxidised margins are hard and resistant to erosion; consequently the root channels weather out in relief from the surrounding sediments.

A sequence, similar to the one described above, persists above 4.570m A.O.D. for a further 2 to 2.5m in MC S to the top of the cliff. It appears that the root channels increase in abundance upwards. This increase in vegetational density suggests progressive stabilisation of the tidal-flat into a marsh (and consequently more terrestrial) environment, under marine-regressive conditions.

Dipping laminated clays - Lithostratigraphic unit 2a (inferentially reworked high tidal-flat)

This unit is developed in MC N, O and P, in what appears to be a hollow on the upper surface of the slump. The contact is traceable westwards to the high tidal-flat/very high tidal-flat junction (junction of units 1a and 2) in MC S. It is probable that unit 2a forms a discrete wedge of material reworked from unit 2, since it contains components derived from the latter. The reworking possibly was due to the NW to W lateral migration of a meander loop of the palaeo-Palnure Burn across the tidal-flats.

The sediment packet deposited in the hollow consists of gently-dipping (5^o - 10^o to the NW) alternating clay and silt laminae and occasional fine sand lenses. The silt is buff coloured and micaceous, and forms prominent bands between clay laminae. Occasional washed-in wisps of carbonaceous matter and grassy material are present but no shell debris. This may indicate that the "palaeo-Palnure Burn" was sited in a very high tidal(and quiet) location.

<u>Mottled and laminated clays - Lithostratigraphic unit 3 (inferentially reworked deposits)</u>

The topmost recorded unit in MC N to R consists of merse deposits that have resulted from further reworking of sediment by the Palnure Burn due to incision under rapidly-falling relative sea-level (or, more precisely, rapidly-rising land). The unit thickens eastwards overstepping progressively older units. It consists of horizontally-arranged greyish-brown clay containing buff to grey coloured silty to very fine sand laminae. The laminae are "wispy", wavy and discontinuous. The clay is frequently mottled and abundant. Scattered bright tan or "rusty" clay nodules add to this effect. There is also a fairly frequent occurrence of carbonaceous patches, twigs and wood, charcoal fragments and peaty horizons. Occasional sub- to well-rounded gravel clasts are present. There are no remains of marine fauna or evidence of burrowing by marine organisms. On the other hand, indurated root channels are frequent.

A dark grey loose clayey soil with abundant present-day root systems is present at the top of logged profiles MC O, Q and R.

C. Meikle Carse section: Logs V to Z (locations NX 4409 6270 to NX 4417 6268

Pale grey clays

Pale grey clay, similar to that recorded further east on the Meikle Carse section, Logs A to M, was noted only at the base of MC V (Appendix p.334) the recorded thickness of the clay being c. 0.30m. The pale grey clay exhibited randomly-oriented carbonaceous wisps and twigs, together with a 0.02m thick gravel and shell band c. 0.08m below its junction with the overlying dark grey-blue clay. The pale grey clay immediately underlying the junction was yellowish green in colour and compact as a result of sub-aerial exposure and weathering.

The junction of the pale grey clay and the overlying dark grey-blue clay is thought to dip eastwards along the section (Fig. 5.6). No pale grey clay was recorded in MC W, although digging showed the approximate altitudinal position of the contact. No pale grey clay was recorded at the base of MC X, but there was a colour change of the "dark grey-blue clays" to pale mid grey towards the base of the log, in association with randomly-oriented plant fragments. This may indicate reworking of typical pale grey clay constituents above a pale grey clay/dark grey-blue clay junction which lies close to (but below) the base of the recorded log.

East of MC X, there is no evidence of the pale grey clay at depth.

Horizontally-bedded dark grey-blue clays with coarse lag deposits

The horizontally-bedded dark grey-blue clays are present at the bases of MC X, Y and Z. The dark grey-blue clays are

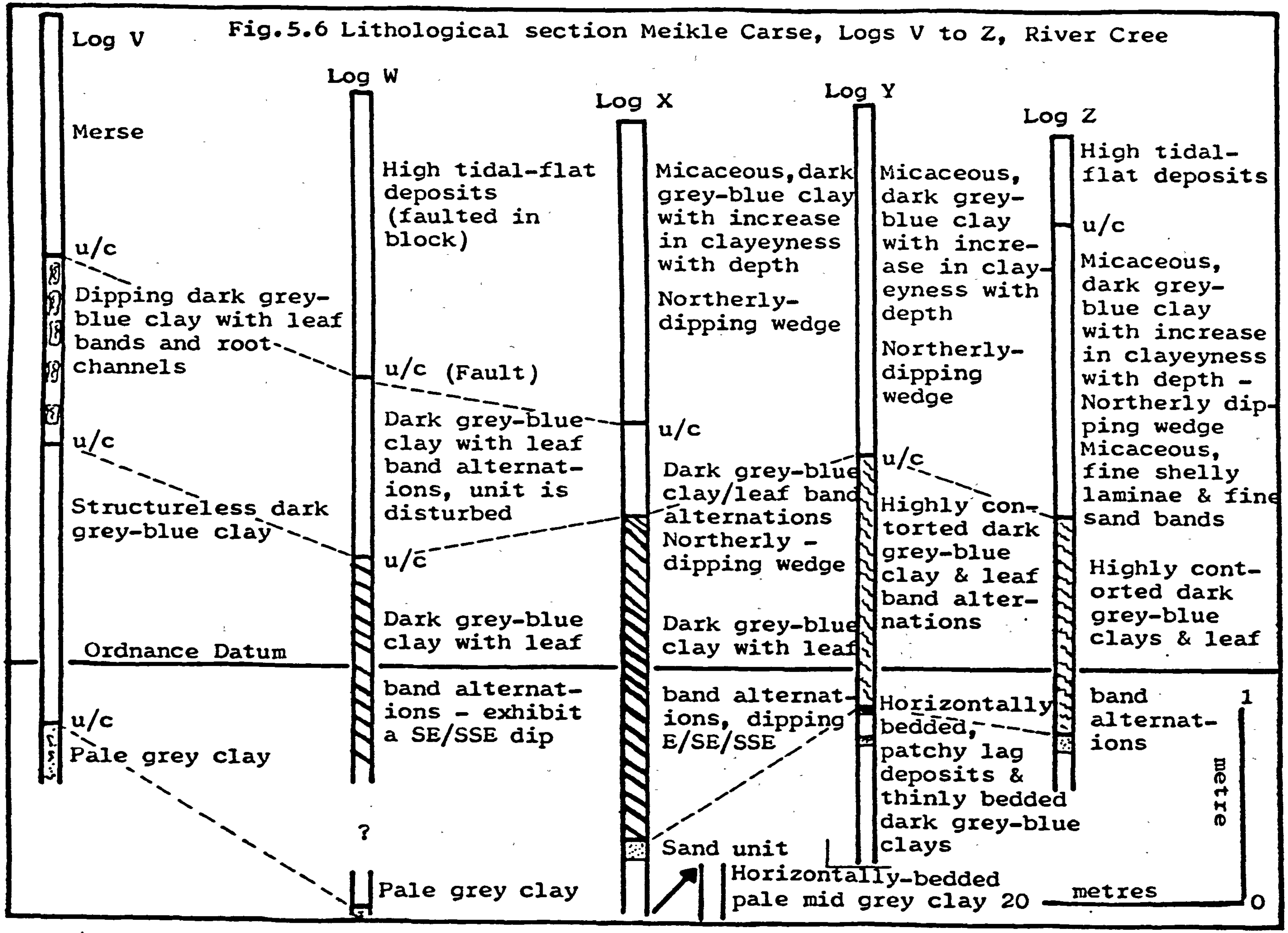


Fig.5.6 Lithological section Meikle Carse, Logs V to Z, River Cree

also present in MC V and W but appear to be structureless.

The dark grey-blue clays under consideration are thinly bedded and they alternate with widespread patchy storm and/or channel lag deposits. Lag deposits consist of an ill-sorted mix of coarse gravel, pebbles and sand with shells and small branches in MC X. They appear to be better developed eastwards, in MC Y and Z. This may imply the onset of channel-floor conditions in this direction. A typical lag deposit in MC Y and Z averages c. 0.05m in thickness and consists of poorly-sorted gravel and sand (frequently pebbly and sub- to well-rounded) and abundant disarticulated bivalves. (chiefly Cerastoderma edule). Small branches and twigs are common, as are large disc-shaped "clasts" of peat, up to c. 0.30m in length and 0.20m in width. It is possible that the lag deposits formed in a shallow channel-floor within a low tidal-flat environment. They are considered to be typical basal point-bar lag type deposits for reasons discussed on page 127 .

Dipping and contorted dark grey-blue clays

These are present from MC U to MC Z. The dark grey-blue clays appear to be structureless in MC V, but, further eastwards, dip progressively more steeply in a general SE direction, becoming folded in MC Z. The structureless dark grey-blue clays of MC V rest unconformably on pale grey clays and consist of c. 1.43m of firm dark grey-blue clay at the base, passing upwards into a micaceous silty clay with finely-crusted shell debris. The top 0.25m of the unit appears to have been reworked and consists of a micaceous mid grey silty clay with washed-in randomly-oriented root channels and plant fragments. The dipping dark grey-blue clays of MC W (base not recorded) comprise 0.15m thick alternations of mid- to dark-grey silty clay, together with micaceous silt and organic (leaf) layers. They dip c. 15° in a SE to SSE direction. The topmost 0.20m of the unit contains finely-crushed shell fragments.

At MC X the dark grey-blue clays (1.66m in thickness) are still dipping in a SE to SSE direction. They rest with angular unconformity upon a horizontal lag deposit of gravel, sand, shells and twigs. The dark grey-blue clay becomes increasingly silty and micaceous upwards, also containing very finely crushed shell fragments.

The dipping alternations of clay and leaf bands become progressively warped and contorted eastwards of MC X. Fine sand laminae and lenses up to 0.005m in thickness are present within the sequence.

At MC Y the clays, reaching 1.29m in thickness, rest on a thin horizontal lag deposit. Dip direction continues to be E to SE but the dip is now steeper, varying from 20^{o} to 30^{o}.

At MC Z, the contorted unit is c. 1.10m in thickness, resting on a horizontally-bedded lag deposit. The alternating dark grey-blue clays and leaf bands have been folded by slumping of this unit as a result of the instability caused by the high angle of dip of the beds. Slow plastic deformation of the clays took place, but initially movement appears to have occurred along zones of weakness or incompetence, present at the junction of the clay beds and numerous coarse-sand bands. As a result, therefore, several wedges of folded clay and leaf bands are stacked unconformably on sand layers. Further evidence of initial sudden failure is provided by the presence of microfaults and fluid-ejection features recorded in this unit.

Since the section terminates at MC Z due to a major landslip of the present-day river bank, it was not possible to trace this contorted unit further eastwards. However, to the east of the recorded section all bedding in the cliff face appears to be horizontal and, c. 10m to the east, extensively-developed horizontal shell bands are visible at the same level as the contorted unit (which is devoid of shell material). This may imply that laterally there is a change in environment at this point. If so, it is suggested that the contorted beds were formed as a result of slumping of a steep point-bar front into an adjacent channel margin. It is further suggested that the point-bar had laterally accreted from a westward or NW position.

Disturbed "zone" of dark grey-blue clays, root channels and leaf band alternations

This unit is present in MC V, W and X as a wedge of thinly-bedded dark grey-blue clays and leaf band alternations with a predominantly NE to N dip. It overlies the dipping and contorted dark grey-blue clays unit unconformably and is itself overlain unconformably by merse deposits in MC V, a down-faulted block of very high tidal-flat deposits in MC W and a further northerly-dipping wedge of high tidal-flat deposits in MC X, which extends to MC Y and MC Z. It becomes difficult to trace the disturbed zone to the east of MC X because beds both in the disturbed zone and in the overlying high tidal-flats are dipping N, the unconformable contact becoming indistinct.

The disturbed zone in MC V is 0.94m in thickness and consists of thinly-bedded dark grey-blue clays and leaf layers dipping NE at 24°. The top surface of the unit exhibits a 0.01m thick crust of reddish oxidised clay, which suggests sub-aerial exposure. The unit is also penetrated by abundant vertical indurated, oxidised root channels. It is difficult to ascertain whether the dipping beds originated as a result of slumping or represent the original surface of deposition. The vertical root channels may be post-slump colonisation. The sediments, however, are those of a high tidal-flat situation, deposited out of reach of the highest storm tides, since no shell material is evident. In MC W the unit is 0.91m in thickness and consists of thinly-bedded dark grey-blue clays and leaf bands. The unit appears to be slightly coarser in grade (silt) at its base. Abundant disoriented clusters of washed-in root channels and leaf lenses suggest reworking of material.

Eastwards of MC W the dark grey-blue clay and leaf wedge becomes increasingly disturbed, warped and gently undulating (but never markedly folded or contorted). Bedding frequently appears to be discontinuous and it is difficult to trace. At MC X typical dark grey-blue clay and leaf band alternations (c. 0.47m in thickness) exhibit a gentle N dip (into the cliff face). The disturbance may be due to post-depositional adjustment of the overlying tidal-flat unit.

Units above the disturbed wedge are diverse and are now described.

Merse deposits - MC V

This unit (1.25m in thickness) is the youngest within the section, but is only present in MC V as the remaining preserved "fragment" of a once more extensive deposit. Most of the patchy merse has been removed by present-day erosion. The deposits are very similar in characteristics to litho-stratigraphic unit 3 (mottled silts and clays) of MC N to U (Chapter 5.2.2.1, p. 127), which occurs at an identical altitude.

In MC V the merse unit rests unconformably on an oxidised clay hard-crust, believed to have formed as a result of subaerial exposure. It is not known how extensive this crust is, but it is reasonable to infer that, during a period of reworking which led to the formation of merse deposits, this subaerially-exposed surface was covered by alluvial deposits formed by fluvial processes.

The merse deposits comprise horizontally-bedded alternations of brown-grey clay (orange-brown when weathered) and buff coloured silt laminae. Occasionally laminae are of very fine sand grade. All laminae are impersistent. Indurated root channels are plentiful, as are modern roots of grasses etc.

Faulted high tidal-flat block at MC W

A c. 1.45m thick block of deposits has been translated westwards and exhibits a faulted contact with the underlying disturbed wedge at MC W. The fault exhibits "normal" movement, with a progressively steepening rotation and warping of dipping laminae (from 12^{o} to 50^{o}) towards "the back" of the fault, to close the gap created by tensional movement.

The deposits themselves consist of eastwards-dipping alternating laminae and bands of tan-grey clay (up to 0.01 to 0.02m in thickness) and buff/orange silt to fine sand laminae c. 2 to 3mm in thickness. Interlaminated with the silts and fine sands are very small organic wisps. No indurated root channels were recorded but there was penetration by abundant present-day grass roots. Additionally, there was no evidence of shell material, implying that the unit was originally deposited above the level of the highest storm tides.

High tidal-flat deposits of MC X, Y and Z

These deposits are 1.53m, 1.80m and 1.51m in thickness in MC X, Y and Z respectively. They consist of northerly-dipping alternations of brown-grey/tan clay and buff silt to fine sand laminae, together with thicker leaf bands and leaf laminations varying from 3mm to 0.01 - 0.03m in thickness. Carbonaceous lenses are evident in MC Y. There appears to be an increase in the clay content down log (in all three logs) and consequently the clay becomes a darker grey-blue colour.

In MC Z, the clays are micaceous and more silty. Silt and fine sand laminae are more abundant, persistent and thicker. Thick bands (c. 7mm in thickness) of rusty orange, fine to medium sand are present at depth. Additionally, accumulations of leaf bands are thicker and more abundant than in the immediately preceding two logs. Leaves are well preserved (e.g. veins can be clearly observed), are whole and not crushed, and therefore are not likely to have been transported a great distance. The high tidal-flats rest unconformably on the horizontally-eroded surface of the laterally-accreting point-bar margin, which exhibits contorted bedding.

The introduction of shell debris into the sequence at MC Z, together with the increase in abundance and grade of sand bands, implies increasing energy levels which may indicate the existence of a channel environment laterally nearby. This suggestion appears to agree with the interpretation of what appears to be evidence of the slumping of the point-bar margin (Chapter 5.2.2.1, p. 128).

A further 0.45m of very high tidal-flat deposits (similar to the faulted block at MC W) is present at the top of the sequence in MC Z. The dark grey/tan clay and buff silt to fine sand laminations and lenses and fine vegetational layers dip in a NNE direction at 30° to 35°. They rest with sharp angular unconformity on the underlying N-dipping high tidal-flat deposits. It is not known whether or not the dip of the uppermost unit represents the original surface of deposition. The unit is penetrated by modern grass roots.

5.1.3 Palnure Burn: Magempsy section

5.1.3.1 Introduction

The Magempsy section constitutes a measured log profile, located on the left (eastern) bank of the Palnure Burn at NX 4584 6590 (Fig. 5.7).

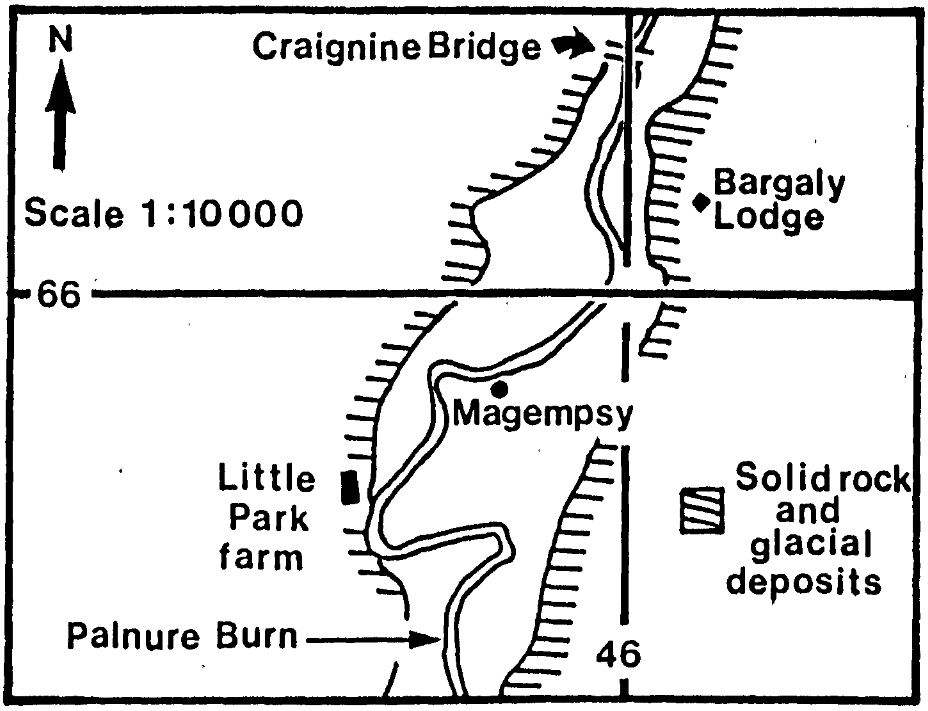


Fig.5.7 Map to show location of Magempsy section, Palnure Burn

5.1.3.2 Description

The measured log, extending from 6.515 to 7.875m A.O.D., consists of pale silver to mid grey, slightly silty clay, which has a sticky consistency and is structureless. Very abundant wood and leaf fragments exhibiting a random orientation are present. There are also occasional wispy laminae of plant material. Abundancy of organic debris increases upwards within the logged profile. At 7.170 to 7.210m A.O.D. and 7.385 to 7.785m A.O.D. are two 4cm thick, laterally persistent, purplish to brown-grey horizontal bands of concentrated leaves, interbedded with 2 to 3mm thick clay laminae forming a "mat". In contrast with the measured part of the section, there is an apparent decrease in organic content from 7.875m A.O.D. to the top of the bank of the stream at 9.875 to 10.375m A.O.D.

5.1.4 Palnure Burn: A75 boreholes

5.1.4.1 Introduction

Investigative fieldwork undertaken by Pre-Construction and Foundation Services Ltd. on behalf of Thorburn & Partners, between Palnure Bridge (NX 4548 6321) and location NX 4580 6291, west of Muirfad farm (Fig. 5.8), involved the sinking of two boreholes and the excavation of four trial pits. The lithology encountered is represented in the NW to SE geological section, Fig. 5.9, which is now discussed.

5.1.4.2 Description of the section

The boreholes and the trial pits all exhibit a bi-partite division of the lithology due to oxidation effects. The boreholes were sunk into carse clays to a depth of approximately 10m (to 5m B.O.D.). At no point was bedrock encountered.

Below a generally thin (c. 0.20m) topsoil, the uppermost 1.5 to 2m of the sediments in the boreholes and pits consisted of a "carse crust" of firm, mottled brown and

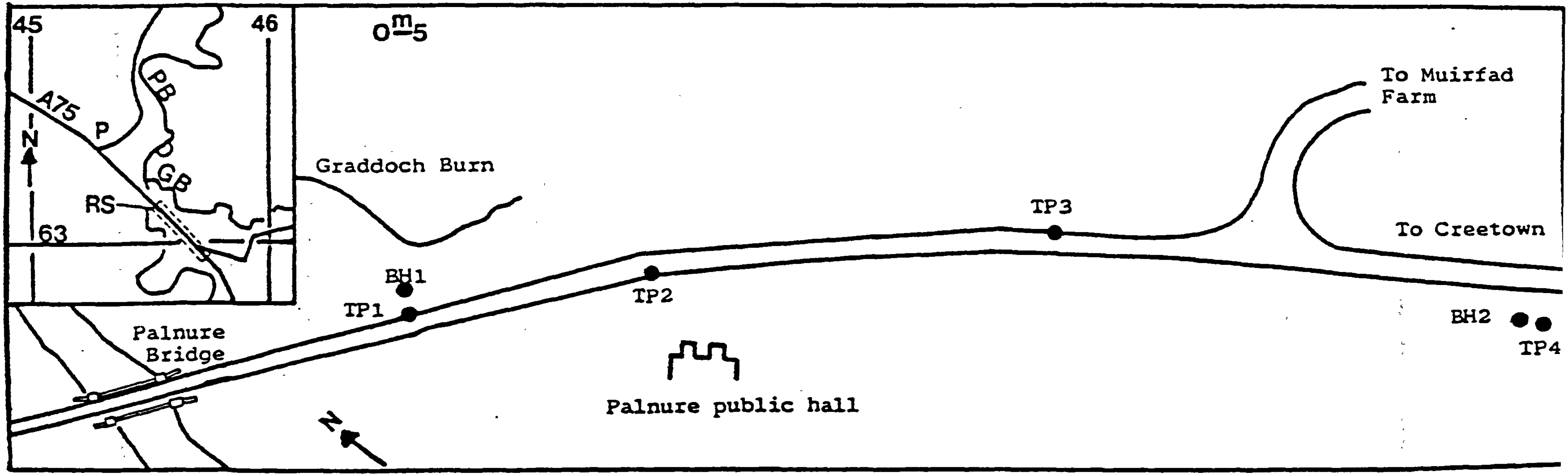


Fig.5.8 Location of boreholes and trial pits, A75 Palnure. Inset: Position of road section (RS) in relation to the adjacent area. BH - Borehole, TP - Trial pit, PB - Palnure Burn, GB - Graddoch Burn, Palnure

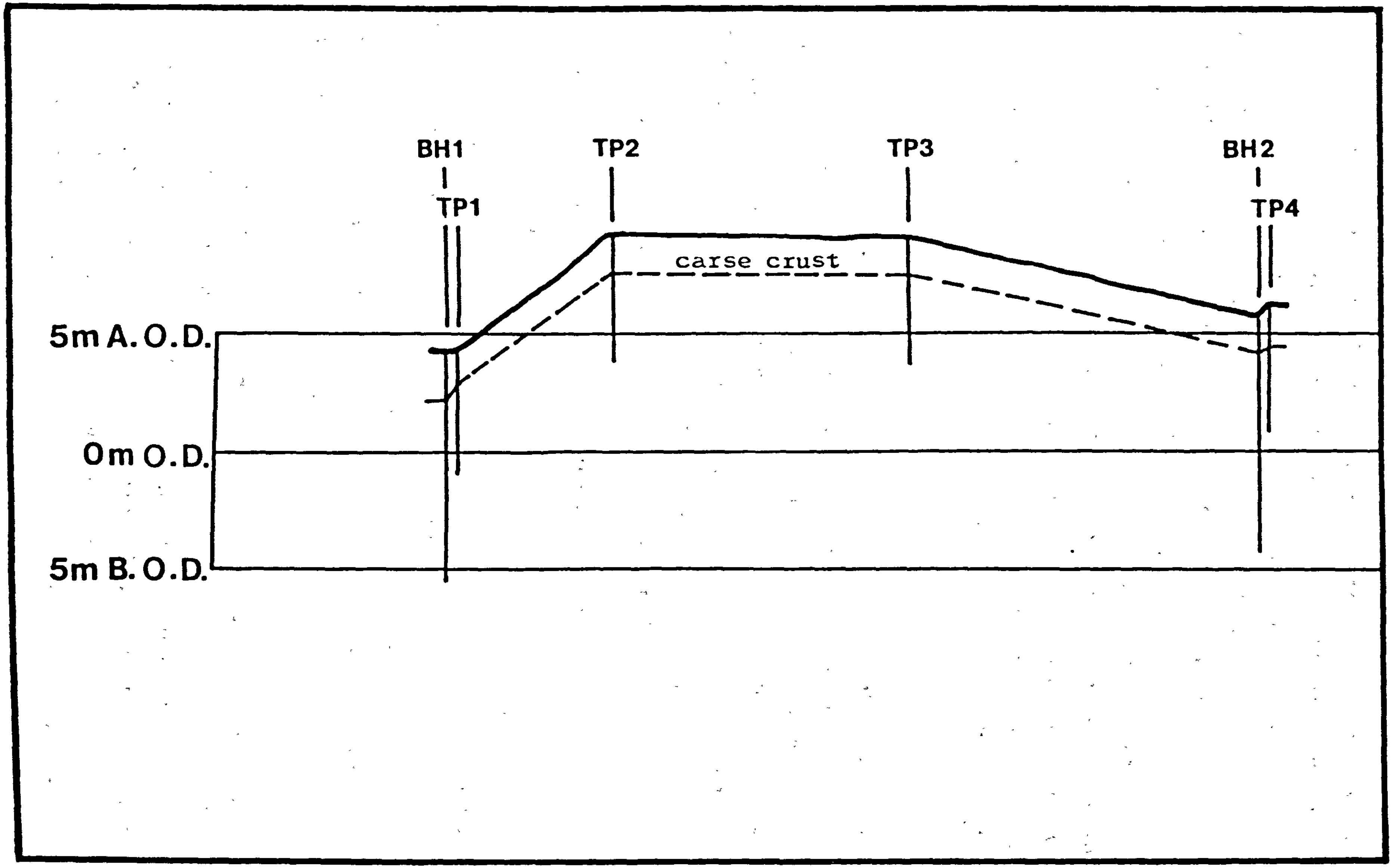


Fig.5.9 Geological section, A75 boreholes and trial pits, Palnure to Muirfad.
Scale Horizontal 1:2500 Vertical 1: 250 (vertical exaggeration 10x)

brown-grey sandy, silty clays, with frequent sand partings, rootlets and decayed vegetation. The mottling in the upper part of the carse clays is the result of oxidation and weathering, greatly assisted by artificial drainage. This condition also accounts for the firm consistency of the upper part of the carse clays. Below 2m, the clay is much softer due to a water content of between 30 and 60% (Sissons, 1967a, p.158). Such clay is often referred to in the older records as "sleech". The clay has abundant carbonaceous inclusion and is rich in vegetable matter. Particle-size distribution curves indicate that the "clay" is composed of 75% silt and 20% clay.

Shell debris recorded in TP4 at an altitude of 4.38m A.O.D. is probably of storm origin, being incorporated into the high tidal-flat deposits from an adjacent channel of the former Palnure Burn. In the sequence recorded in BH 1, coarse to fine rounded alluvial gravel clasts are present within the near-surface silty layers, together with some rootlet material. The gravel is derived from the adjacent Graddoch Burn.

5.1.5 Palnure Burn: Muirfad meander section

5.1.5.1 Introduction

The Muirfad meander section trending approximately W to E and comprising nine log profiles (Appendix p.340-344) is situated on the outer bank of the Palnure Burn, between locations NX 4541 6281 and NX 4554 6277, SE of the A75 Palnure road bridge (Fig. 5.10 and Fig. 5.11).

The profiles are of variable depth-range, but over the whole section extend from 0.735m B.O.D. to 4.460m A.O.D. The section, 94.55m in length, records the presence of a sequence of deposits ranging from pale grey clays representing high tidal-flat or boggy conditions prior to the Flandrian marine transgression, to fining upwards, interbedded sands, fine to pebbly gravels, muds and organic debris, representing a

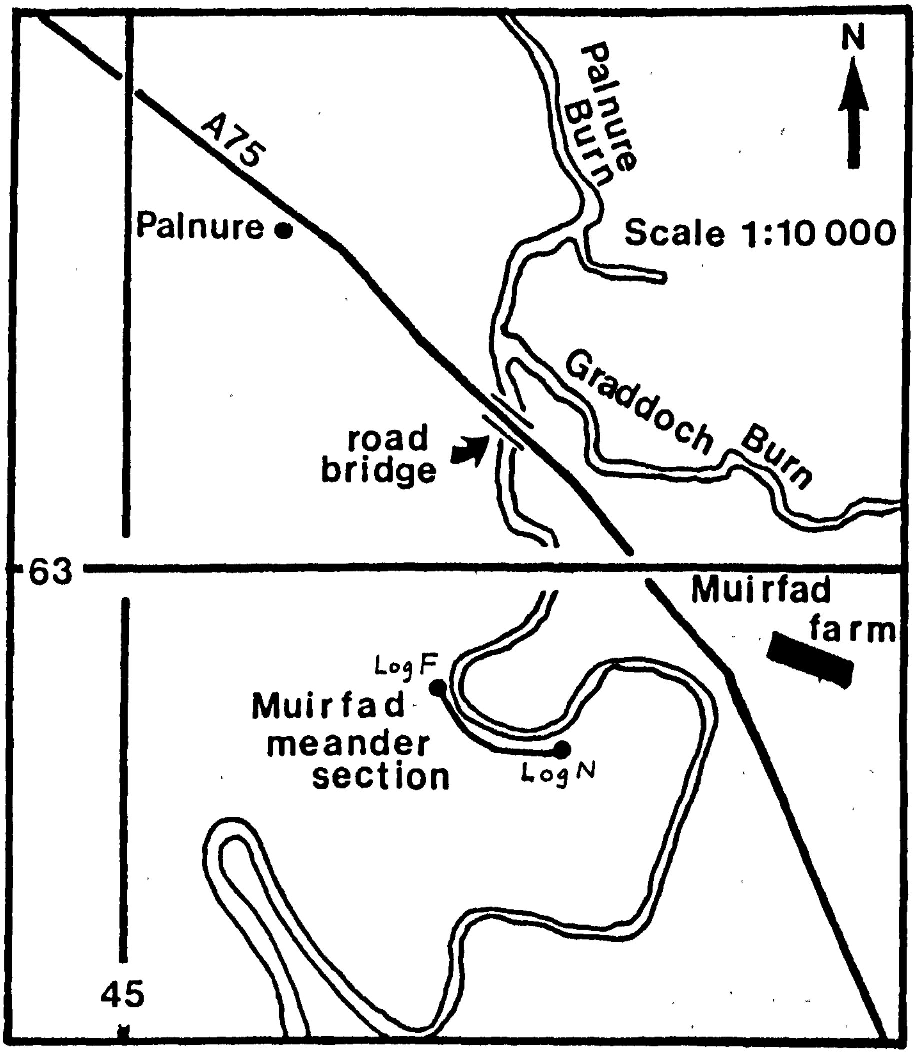


Fig.5.10 Map to show location of Muirfad meander section, Palnure Burn

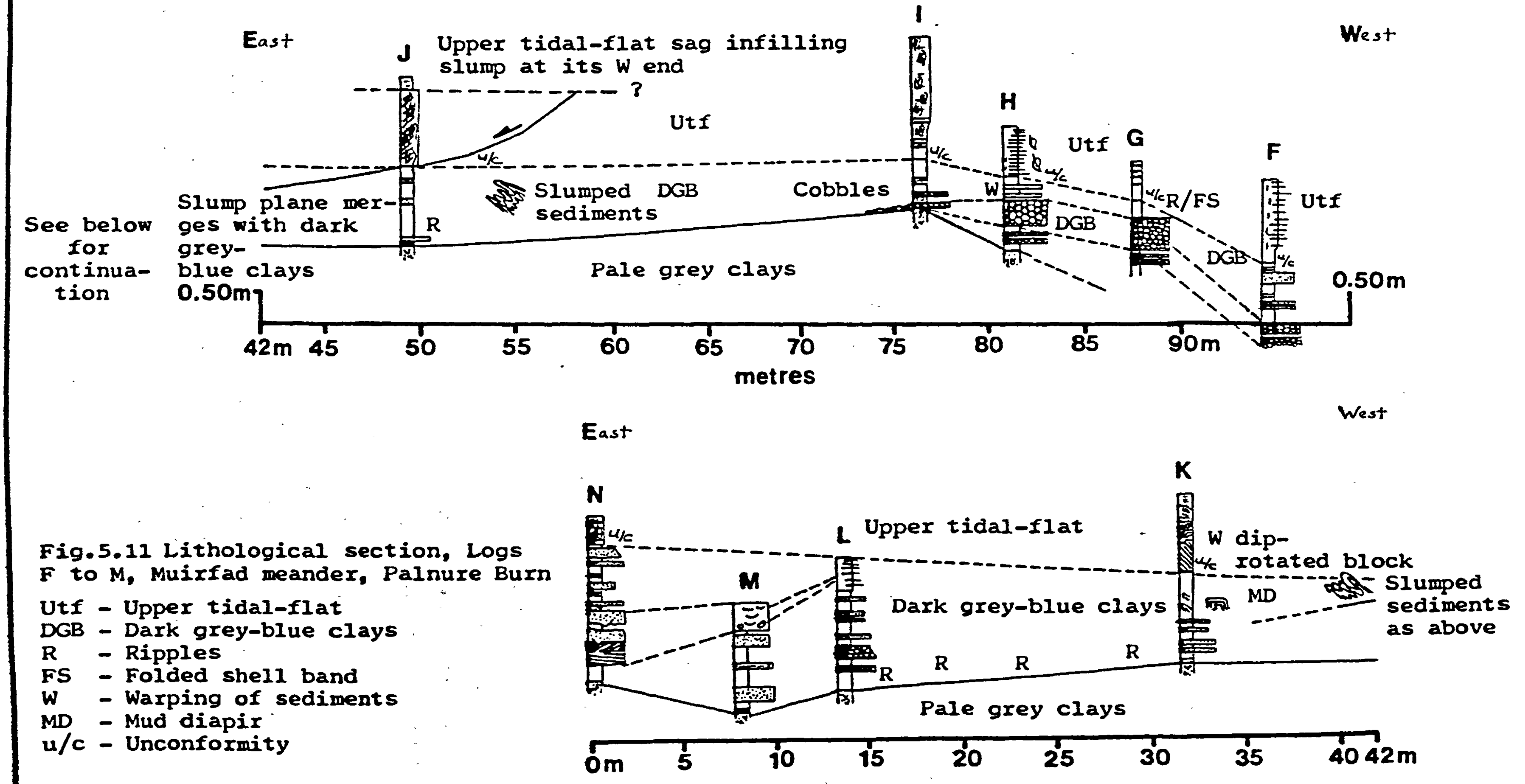


Fig.5.11 Lithological section, Logs F to M, Muirfad meander, Palnure Burn

Utf - Upper tidal-flat
DGB - Dark grey-blue clays
R - Ripples
FS - Folded shell band
W - Warping of sediments
MD - Mud diapir
u/c - Unconformity

laterally-migrating channel-infill sequence. The sequence is disturbed at two locations due to rotational slumping of overlying tidal-flats, one example of which is perfectly preserved. This movement has led to the contortion of channel-floor material. The channel-infill sequence and overlying progradational high tidal-flat deposits (consisting of laminated silts, clays and sands) are in turn overlain by marsh deposits which have been subject to the effects of post-depositional compaction and settling.

5.1.5.2 Description

Pre-Flandrian transgression pale grey clays

The pale grey clays, present in all log profiles except F and G, have lithological characteristics similar to those of the pale grey clays of the Parkmaclurg borehole (Chapter 5.1.1) and Meikle Carse section (Chapter 5.1.2). An average thickness of c. 0.15m was recorded but the base of the clays was not observed. The clays contain abundant unoriented plant remains and carbonaceous wisps and, as in the other sections where they occur, are believed to represent upper (or high) tidal-flats or a boggy marsh environment.

Between log profiles K, L and M, mud ripples are evident on the unconformable contact surface of the pale grey clays and overlying dark blue-grey clays. The mud ripples are straight to slightly sinuous with flattened tops (? evidence of bi-directional currents). Their orientation and mode of formation are discussed in Chapter 5.2.5, when environmental interpretation is considered.

The contact between the pale grey clay and overlying dark grey-blue clay with interbedded gravels is unconformable and sharp throughout. At Log I the contact is marked by medium to coarse channel-floor gravels, which develop westwards. Channel-floor or transgressional lag material (such as rounded peat slabs and lenses, cobbles and shell bands or pockets) is evident within and at the base of the dark grey-blue clays throughout the length of the section. A peat lens was noted in Log J, whilst a laterally-persistent shell band was noted between locations K and L.

Dark grey-blue clays and coarse gravels

The dark grey-blue clays and interbedded gravels are present in all nine log profiles. They represent channel-floor and channel-infill deposits. Channel-floor material is recorded at the base of all the log profiles. Channel-floor bar material is present in Logs F to I (see Fig. 5.11). The development of a fining-upwards channel-infill sequence (due to a laterally-migrating channel) occurs between Logs L and N (Fig. 5.11).

The dark grey-blue clays average 1.50m in thickness. In Logs F to I (Appendix p.340-341) the thinly-bedded dark grey-blue clays are interbedded with poorly-sorted, largely clast-supported coarse gravels, with cobbles and shells thought to represent channel-floor bar material. In Log F, there is some patchy matrix of finer gravel. The coarse gravel with cobbles fines rapidly up-log to fine to medium gravel bands and impersistent lenses with abundant shell material. Approximately 35% of the latter is articulated and of storm origin although, being articulated, the shells have not been transported a great distance from a living colony. Generally, the shells are an ill-sorted mix of crushed, and whole but disarticulated, valves of adult and juvenile forms. They consist mostly of *Cerastoderma edule*. At *c.* 0.10m W of Log F, between 0.165m and 0.265m A.O.D., is a community of *in situ* *Cerastoderma edule* in life position. The assemblage is a living one with adults and juveniles in all stages of growth.

The nature of the contact between the dark grey-blue clays and overlying (tidal-flat) slump unit is discussed on page 90.

The channel bar material in Log H is well-developed, consisting of a 0.45m thick upward-coarsening unit of poorly-sorted, part clast, part matrix-supported, well-rounded coarse gravel and cobbles - probably derived from fluvio-glacial deposits. The matrix is composed of medium to slightly coarse gravel. Shell material is concentrated on the upper surface of the gravels - a common occurrence on the surface of channel-floor bars on the present-day River Cree, e.g. at Blackstrand side-bar (Chapter 10.2.3.1).

The channel-floor bar unit is traceable westwards to Log F, and eastwards as far as Log I, where it rests directly (and unconformably) on the pale grey clays. There is evidence of stratification within this unit and the underlying dark grey-blue clays. The interbedded gravels of the dark grey-blue clays above the channel-floor bar unit are of fine gravel grade and contain folded shell lenses, as the clays have been disturbed by slump action directly above them.

The channel-floor bar unit is considerably thinner at Log I. It is composed of ill-sorted medium to coarse gravel and cobbles, but is now only 0.05m in thickness resting on pale grey clays, and probably representing a channel-floor margin. Above this unit, the clays are interbedded with coarse sand and fine gravel. Storm-deposited shell bands are of similar composition to those in other log profiles, but the gastropod Hydrobia ulvae was recorded as being present, thus suggesting that the environment was estuarine.

At Log J, slab-shaped derived "peat" cobbles occupy the base of the channel. At 1.26m A.O.D. (c. 0.20m above the pale grey clay / dark grey-blue clay junction), mud ripples were recorded on the surface of the thinly-bedded dark grey-blue clays. Bands of uncrushed shell are present within the middle and lower parts of the dark grey-blue clays. The upper half of the unit contains bands of shell debris crushed and compacted as a result of disturbance due to slump movement above. The contact with the overlying unit is abrupt.

At the base of Log K, there is a considerable number of reworked, disc-shaped peat slabs of cobble grade. The overlying 0.70m of dark grey-blue clays contain layers of storm-gravel composed of whole but disarticulated Cerastoderma edule valves. The upper 0.90m of the dark grey-blue clays contain shell material which was crushed and compacted prior to folding - the latter of which resulted from overlying slump movement.

Between Logs K and L, the onset of a planar development of laterally-extensive shell and gravel beds and cut-and-fill units is recorded. The beds and units thicken and dip gently (less than 10^{o}) in a general E to ESE direction, indicating the lateral migration of a river channel at right angles to this general direction, i.e. the channel has migrated in a SW direction. The cut-and-fill units, of variable thickness, have a low relief (but never greater than 0.04m), and an irregularly-eroded lower surface. The channels are infilled with fining-upwards coarse to fine gravel and unoriented crushed and whole valves of Cerastoderma edule and Tellina sp. Whole valves of Mytilus edulis and spiny Cerastoderma edule were also noted. The shells are relatively unworn and appear to have undergone little transportation to their sites of deposition. The death assemblage is storm-derived from a more marine but not very distant source.

The channel units also show a general fining-upwards within the channel-infill sequence. They are frequently well-compacted and occasionally semi-consolidated due to the weight of the overlying interbedded clays, which exhibit an abrupt, regular planar contact with the gravels. The consolidation of the gravels is also aided by the presence of iron in solution, which stains and coats the gravels and cements the clasts.

The channelled units are interbedded with thinning-upwards (to the next channelled unit) medium (c. 0.30m) to thinly-bedded (less than 0.10m) clays.

Log L provides a good example of a fining-upwards channel-infill sequence on a large and small scale. The lowest cut-and-fill unit (c. 0.18m in thickness) consists of fining-upwards medium gravel to very coarse sand. Clay flakes or rip-up clasts are incorporated into the unit. There is also a tendency for shell material to be concentrated towards the top of the gravels. A peat cobble was noted at c. 2.08m A.O.D. The topmost 0.50 to 0.60m of the sequence consisted of a finer channel-infill of interbedded and upwards-fining coarse- to fine-sand bands and dark grey-blue clays. Silt laminae are also evident in the topmost 0.35m of the sequence. The channel and overlying tidal-flat contact was not recorded.

As in Log L, Log M records a channel-floor and channel-infill sequence. The lowest channelled unit in Log M can be traced to Log L. It extends eastwards beyond Log M but is lost below the level of the Palnure Burn, and is covered by present-day river sediments.

The channelled units of Log M are similar to those previously described, containing fining-upwards coarse to fine ferruginous gravel, which is sub- to fairly well-rounded and structureless, together with shells in variable abundance. No evidence of cross-stratification is observed - possibly due to the fact that the gravels, when deposited, were of too coarse a grade and were not cohesive enough. The only hint of channel orientation and current directions is given by the presence of oriented twig material, present in two of the channelled units (for discussion see Chapter 5.2.5). Additionally, small-scale mud and silt ripples were noted in the interbedded muds at two levels. Their orientation appears to be in conflict with that of the twig material (see discussion, Chapter 5.2.5).

The thickest channelled unit is recorded in the top 0.45m of Log M. It can be traced laterally westwards to Log L where it thins and fines to a coarse-sand grade band at c. 2.58m A.O.D. Eastwards, the unit thickens and continues to Log N, being found at 0.915 to 1.765m A.O.D.

At M, the 0.45m thick unit consists of poorly-sorted, structureless fine gravel, with occasional medium-grade gravel and storm-derived pockets of shell material. Oxidised clay flakes (rip-up clasts) are present, together with cobble-grade clay "concretions". The well-rounded cobbles are c. 0.10 to 0.14m in diameter and have a 0.05m wide rim or coating of indurated iron. They are found in the lower part (i.e. the floor) of the channelled unit.

Between Logs M and N at c. 0.840 to 0.890m A.O.D. (in the dark grey-blue clays), mud ripples were recorded on a bedding plane. Their orientation and significance are discussed in Chapter 5.2.5.

As previously noted the already-discussed channelled unit of Log M expands to a thickness of 0.85m in Log N, the last of the nine profiles to be recorded. The basal channel-floor deposits here show the only evidence of bi-directional (herringbone) stratification recorded (hence confirming a tidal situation). Resting abruptly on dark grey-blue clay is 0.19m of medium-grade (pebbly) gravel exhibiting low-angled planar cross-stratification, with individual units c. 0.02m thick. The dip is in a general W to WNW (or possibly NW) direction. Upwards there follows a sharp contact with the overlying unit of planar cross-stratification (within the same medium-grade gravel), which dips at c. 18° E to ESE - SE, in the opposite direction. Again individual cross-strata are 0.02m in thickness. The medium-grade pebbly gravel grades upwards into structureless finer-grade gravel and shells, as a result of waning current flow.

There then follows a further fining-upwards channel-infill sequence of fine-grade gravel to medium-grade sand, intercalated with clays and bands and pockets of shell debris. Oriented, washed-in branch fragments were located at N, between 2.115 and 2.465m A.O.D. The surface of the branch debris is frequently pitted with "V"-shaped "skip" marks or nicks produced by abrasion of the branches by sharp objects when undergoing transportation. Wood would be easily marked when wet. Circular impressions of shell valves are also evident, the valves having become adhered and pressed into the surface of the wet wood when buried in mud at depth and subjected to pressure from the overlying sediments.

An abrupt unconformable contact with the overlying tidal-flat, which is relatively undisturbed, occurs at c. 3.135m A.O.D.

Beyond Log N, as far as location NX 4558 6280, the channel-floor and infill deposits gradually thin in a NE direction. Channel-floor deposits, similar in composition to those previously described, extend for c. 1m from 0.59 to 1.59m A.O.D. They are overlain by a further 1m of extensively-warped and folded leaf bands and pale green-grey clayey silt alternations which contain finely-crusted shell fragments. These slumped tidal-flat deposits are dipping steeply in an approximately westerly direction.

The dark grey-blue clays are interbedded with pockets of structureless, channelled gravel (which fines upwards to coarse sand), containing washed-in debris such as oriented branch, twig, hazel-nut and bone material (discussed in Chapter 5.2.5), shell debris and peat, together with leaf lenses. The wood and nut material exhibits a patchy development of bright blue vivianite. The bed thickness of the clays varies from medium at the "base" of the sequence to thin near the junction of the channel unit and the overlying tidal-flats. The clays also appear to be horizontal in attitude. Shell debris, which is totally unoriented within the gravel pockets, is composed of crusted and disarticulated whole bivalves such as Cerastoderma edule (c. 60% of the total shell composition), Mytilus edulis, Tellina sp. and Pholadomya sp. Within the clays, however, the bivalves are often arranged convex up, as single layers on the bedding planes. There appears to be an equal mix of adult and juvenile forms. Therefore, as there has been no sorting, the death assemblage has not been transported a great distance from the established colony. A portion of the shell debris, however, appears to be of an older derivation since valves are heavily stained by iron cements and were probably eroded from already-consolidated gravel pavements.

Gastropods were also recorded as being present, but not in abundance. Littorina littorea and Littorina littoralis were noted, the former species exhibiting perfectly circular holes (c. 0.025mm in width) drilled through the valves as a result of boring by another organism. This suggests that the material is derived by erosion from already deposited sediment. Furthermore, examples of Turritella communis exhibiting encrustation of the shell by annelid tubes indicate that the shell had been both unoccupied and uncovered by erosion of sediment prior to transportation, deposition and burial in the tidal river-channel deposits. The fact that the shells are completly unworn suggests that they were not subject to very high energy conditions for a lengthy period of time.

Laminated clays, silts and sands

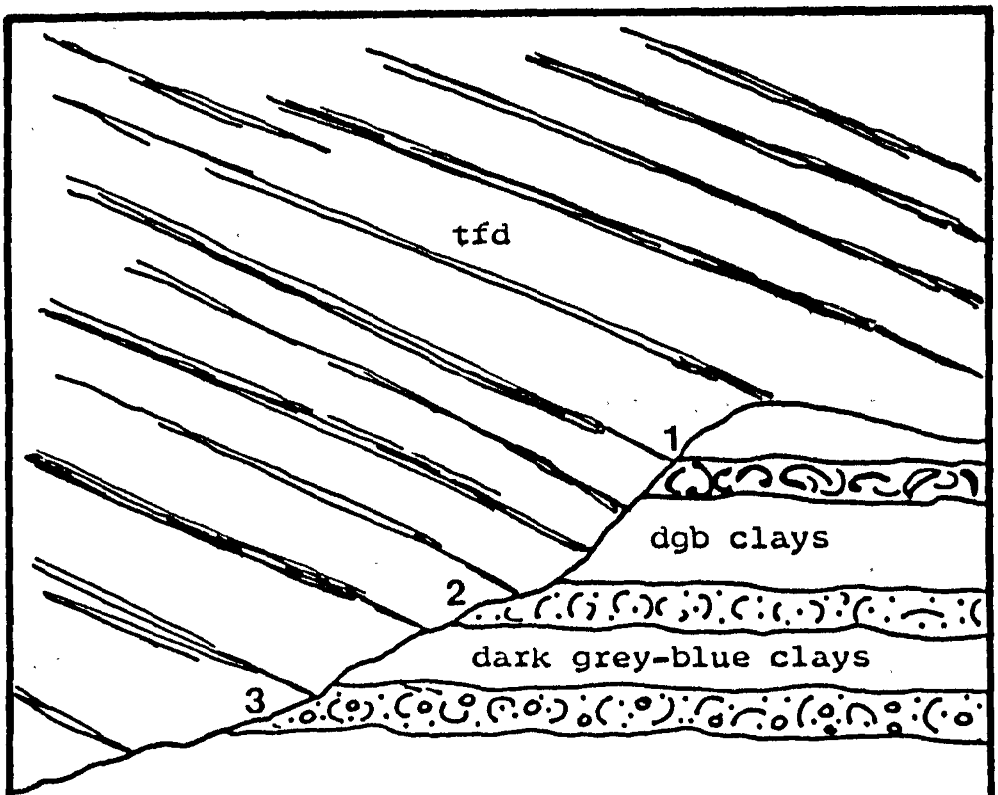
The laminated clays, silts and sands represent high tidal-flat to marsh deposits which are disturbed by slumping, post-depositional sagging and warping. The deposits are present in all logs except Logs L and M, which exhibit a channel-floor and channel-infill sequence only. The thickest development of tidal-flat and marsh deposits, 1.99m, was recorded in Log I.

The nature of the contact between the dark grey-blue clays and the overlying disturbed tidal-flat deposits throughout the section is now described.

At Log F, the most westerly of the section, the contact of the dark grey-blue clays and laminated silts of the tidal-flats is unconformable, sharp and slumped. The laminated silts have undergone downslope movement, the direction of which is difficult to establish, but is possibly north-eastwards (see discussion, 5.2.5). At F the laminated silts abruptly truncate successively lower coarse sand and shell bands of the channel deposits (Fig. 5.12). This contact is traceable eastwards to Log G, where the surface (i.e. the top of the channel-floor dark grey-blue clays) is rippled. The mud ripples are symmetrical, parallel and of low amplitude (c. 1.00 to 1.50cm) with a wavelength not greater than 0.10m. The significance of their orientation is discussed in Chapter 5.2.5. Immediately below the contact, the channel-floor muds (c. 0.30m in thickness) exhibit folded layers of shell debris as a result of disturbance by the overlying slumped unit. The contact continues to downcut eastwards to Log H where it becomes horizontal. Noticeable warping of the channel deposits to a depth of c. 0.32m below the contact has occurred. At Log I the contact of the channel deposits and tidal-flats was sharp and horizontal. No disturbance of the underlying channel clays was noted.

The contact discussed above could not be traced with certainty as far as Log J. Although occurring at a similar level in Logs J and K, the contact is part of a larger, discrete rotational slump, which is well preserved in the river bank face (see Fig. 5.11).

The downslope translation of tidal-flat deposits into a flanking channel between J and K, along a low-angled rotational surface of failure, has resulted in:



1 shell band (0.01m in thickness)
2 coarse sand/shell band (as above in thickness)
3 very coarse sand, fine gravel/shell band
(0.08m in thickness)

NB Abrupt truncation of channel deposits (at 1,2,3) by overlying slumped tidal-flats

Fig.5.12 Contact of horizontally-bedded channel deposits with gently-dipping tidal-flat deposits in the vicinity of Log F, Muirfad meander, Palnure Burn. tfd - gently-dipping tidal-flat deposits composed of laminated silts and leaf-layer alternations. Distance across sketch c. 0.80m

(a) The plastic deformation of the underlying still-soft channel-floor muds, manifesting itself as folded clays and shell bands, together with the appearance of mud diapirs,

(b) A complex brittle failure of the less-cohesive tidal-flat deposits.

The latter process resulted in:

1. Backward westwards rotation and plastic deformation of lowest tidal-flat deposits into the curved low-angled slip surface immediately east of Log J.
2. Forward eastwards rotation and tilting of tidal-flat deposits (located at the "back" of the slump) at J.
3. The presence of several unconformable blocks at Log K.

The rotational slip surface is c. 22m in length. The slump is, therefore, considered to be of large scale, comparable in size with those recorded and observed on the present-day River Cree estuary at Meikle Carse. In the slump recorded in the Muirfad meander section, the surface of failure passes down through high tidal-flat deposits into channel-floor sediments (which are folded), and then becomes difficult to trace, as it merges with the bedding of lower-lying deposits.

The top of the slump was noted in Log J at 2.600m A.O.D. Although not investigated above this altitude, deposits overlying the rotated blocks appear to have originated in a high tidal-flat or marsh environment. They appear to have been deposited normally, i.e. horizontally, but were affected by warping and sagging as the slump was stabilised and the sequence settled. It is possible that the tidal-flats have downwarped to infill the "gap" created at the back wall of the slump, by downslope movement of material. This, however, has not been confirmed. Eastwards from Log N, the slumped upper tidal-flats appear to dip in a general westerly direction. The deposits are warped and rest abruptly on channel-floor sediments. The tidal-flats here are believed to form the NE flank of a channel, laterally migrating in a SW direction (see discussion in Chapter 5.2.5).

Lithological Description: Laminated silts, clays and sands

The high tidal-flat and marsh deposits generally consist of pale to mid grey, micaceous clayey silts with non-persistent fine to medium sand laminae and lenses. The silts are frequently interbedded with warped leaf layers, organic laminae and rounded leaf balls, and are penetrated by frequent to abundant vertical indurated root channels of a patchy distribution (e.g. as in Logs F, I, J, K, N). Finely crushed, unoriented shell material occasionally is present (e.g. Log H).

In Log J the high tidal-flats were preserved in a steeply-dipping (to the east) rotated block. Vertically-oriented root channels truncate the steeply-dipping laminae, indicating a post-slump colonisation of the block by vegetation (probably reeds).

Deposits abruptly and horizontally overlying the top of the slump include pale tan-grey clay and fine organic intercalations, together with occasional laminae of sand. Gentle sagging of the deposits is indicated by the undulatory or warped nature of the laminae and organic bands. There are no shelly remains present.

East of Log J, immediately above the junction of the slump and channel deposits, high tidal-flat beds are rotated or warped backwards (i.e. they dip westwards) into the low-angled slip surface.

Examples of plastically-deformed channel-floor muds were recorded between Logs J and K. Folded floor sediments are further truncated by unconformably overlying series of blocks.

Rotated blocks are also recorded at Log K where at least four units overlie the disturbed slumped sequence. The upper unit appears to drape the previous one, indicating an original surface of deposition.

Slumped upper tidal-flat deposits at Log N and eastwards are similar in composition to those previously described but belong to the slump which is moving westwards (discussed this Chapter 5.2.5.2 ,page 90).

5.1.6 Palnure Burn: Long Loop section

5.1.6.1 Introduction

The Long Loop section, trending N to S and comprising five log profiles (Appendix p.345-347), is located between locations NX 4523 6244 and NX 4524 6238 on the inner bank of the Palnure Burn, c. 200m north of its confluence with the River Cree (Fig. 5.13).

The profiles recorded vary from approximately 3.5 to 4.75m depth, and extend from 0m O.D. to 4.845m A.O.D. The section (Fig. 5.14) records the presence of a sequence of deposits ranging from dark grey-blue clays (base not observed), containing variable amounts of medium to coarse gravel and cobbly material, together with shell bands and twig debris. The dark grey-blue clays and coarse gravel unit represent deposition in a channel-floor and/or very low tidal-flat environment. These units pass abruptly upwards into grey silty clays and clayey silts with patchy mica and indurated root channels, which represent upper tidal-flat deposition. Above c. 3m A.O.D., with the introduction of fine sand laminae, there is a general increase in sand proportion up-log. The topmost 1.50 to

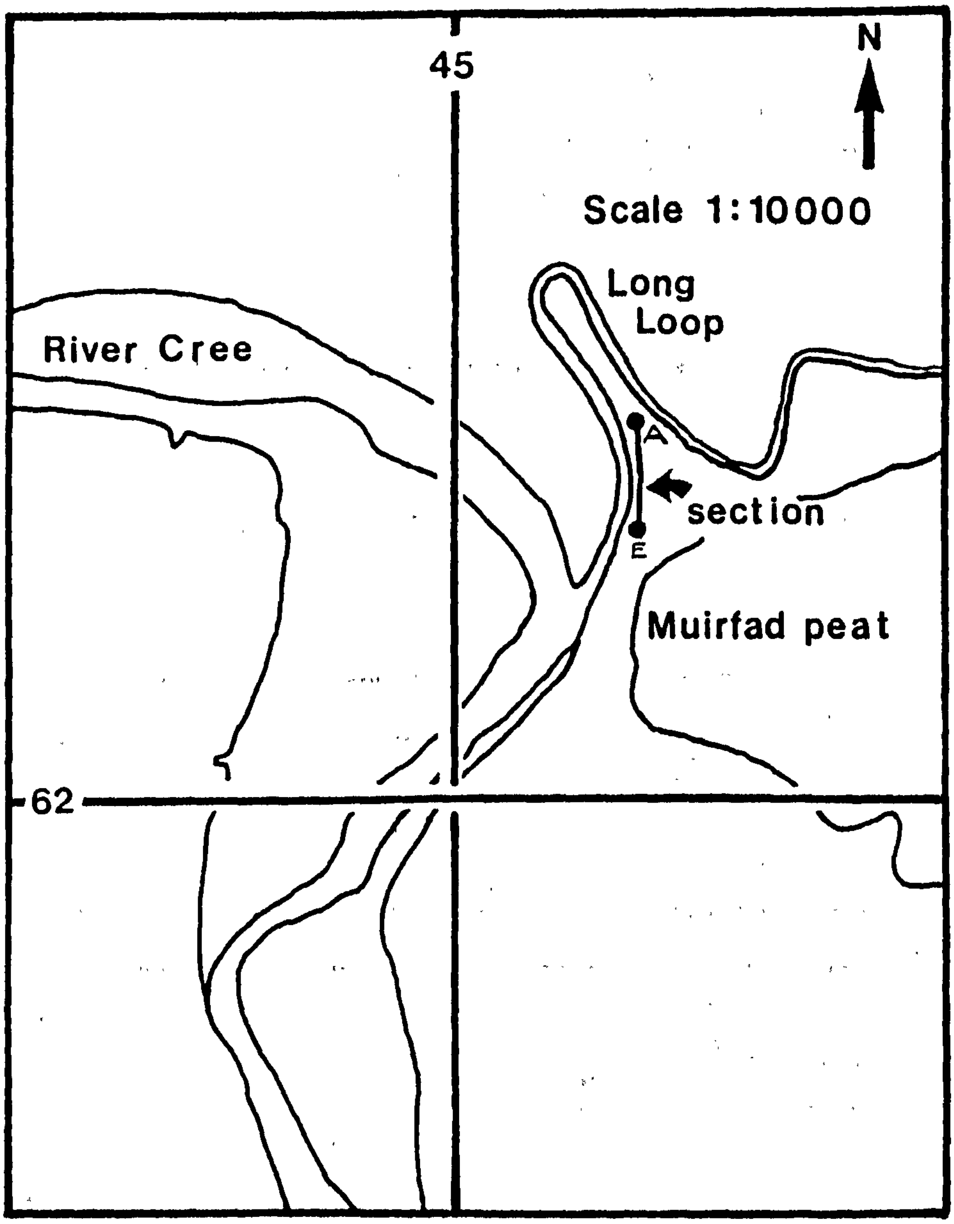


Fig.5.13 Map to show location of Long Loop section, Palnure Burn

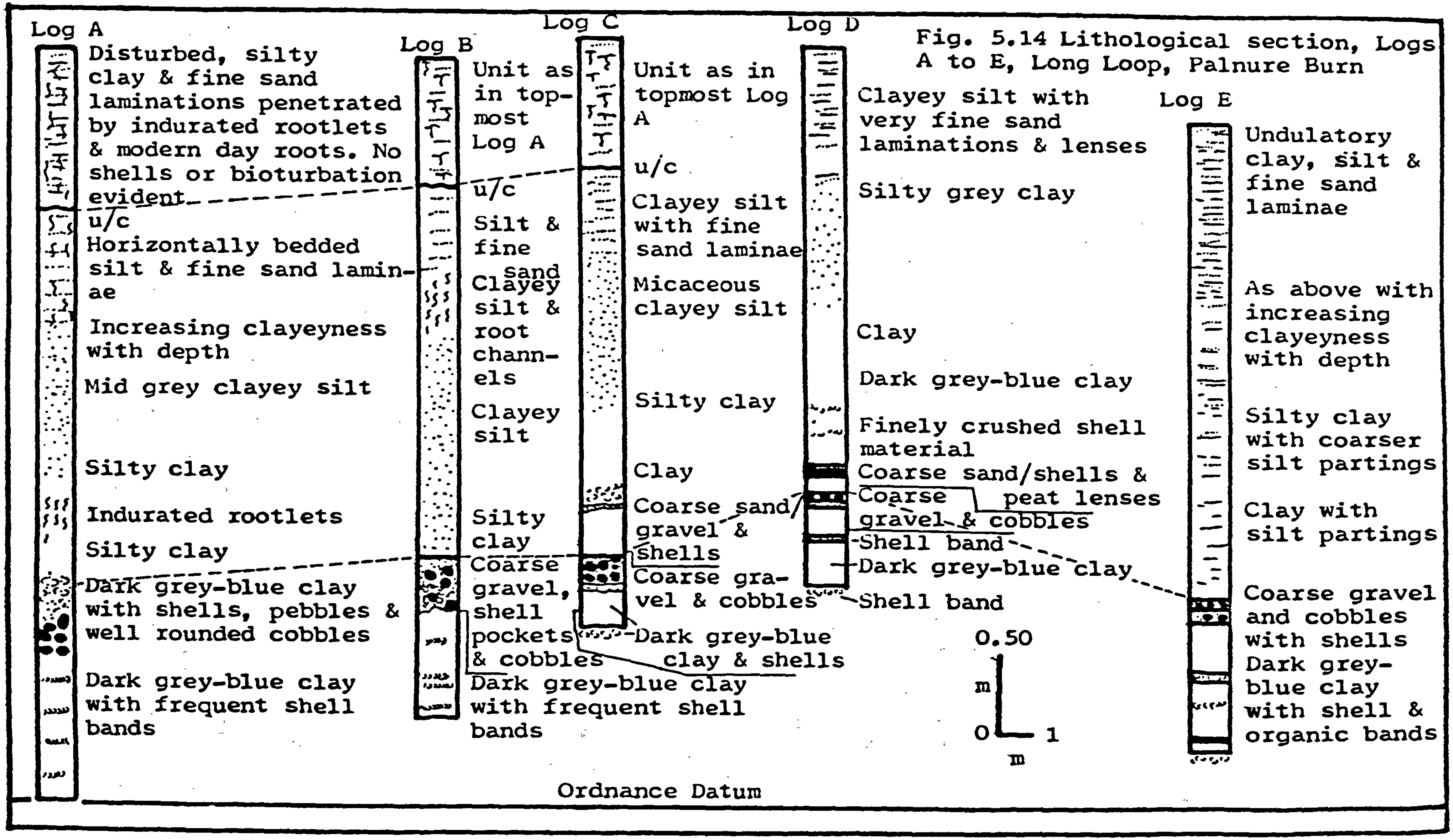


Fig. 5.14 Lithological section, Logs A to E, Long Loop, Palnure Burn

2m consist of repeated units or wedges, bounded by unconformities of laminated clays, silts and sands typical of an upper tidal-flat situation.

5.1.6.2 Description

Dark grey-blue clays (Stratigraphic units 1 and 1a)

The dark grey-blue clays, identical in nature to those of the Meikle Carse section, are present in all five logs. They vary from 0.83 to 1.48m in thickness; their lowest altitudinal occurrence is at 0.005m A.O.D. (Log A), the highest at c. 2.895m in Log D. Since the base of the clays is not recorded, it is not known if the pale grey clays observed in other sections (i.e. Meikle Carse and Muirfad meander) are present at depth. The boundary of the dark grey-blue clays with the overlying grey silty clays is unconformable (see Fig. 5.11, this chapter). The latter clays rest on a unit of interbedded coarse gravels and cobbles in Logs A and B, and upon dark grey-blue clays in Logs C, D and E. Contacts are sharp throughout. The dark grey-blue clays below the coarse gravel and cobble unit contain impersistent, horizontal bands of finely-crushed, fragmented and disarticulated but whole shell valve material. The majority of shell bands are composed of juvenile to young adult Cerastoderma edule valves, disarticulated but not well worn. They are positioned convex up. Occasional bands are composed of valves of Scrobicularia sp. These are disarticulated, whole and worn, and have undergone lengthier transportation than the Cerastoderma edule material. The coarse gravel and cobble unit itself, believed to represent storm-derived channel-floor lag material, is present throughout the section. It varies from 0.05m (Log D) to 0.35m (Log B) in thickness and is composed of ill-sorted sediment ranging from coarse gravel to pebble in grade, together with frequent, very well-rounded cobbles, derived from local fluvio-glacial deposits. The 0.35m thick unit in Log B fines upwards from a cobble and coarse gravel base, set in a finer gravel matrix with shell pockets, through to coarse gravel and fine sand. Pockets of washed-in twig and leaf material are also present. Branch material, oriented NE - SW at the base of the unit, has been rolled along the channel floor. The dark grey-blue clays above the channel-floor gravels contain relatively few bands of finely-crushed and whole shell fragments. At c. 1.75m A.O.D. in Log D there are washed-in lenses of peat.

Grey silty clay to grey clayey silt
(Stratigraphic unit 2)

The grey silty clay rests abruptly on the channel-floor unit of the dark grey-blue clays in Logs A and B, and on dark grey-blue clays (probably very low tidal-flat in nature) in Logs C, D and E. The grey silty clay varies from 0.70 to 1.25m in thickness. It darkens in colour with depth. On a small scale it appears to be structureless, apart from occasional silt laminae recorded in Logs A and C. The lowest altitudinal evidence of indurated root channels was recorded in Log A between 1.705 and 1.905m A.O.D. The grey silty clay passes upwards into pale to mid grey clayey silt (i.e. there is an increase in the proportion of silt up-log).

Grey clayey silt (Stratigraphic unit 2)

The above unit varies from 0.70 to 0.80m in thickness in all logs except in Logs D and E, in which it is absent. In the latter Log the grey silty clay is overlain unconformably by laminated clay, silts and sands (see discussion Chapter 5.2.6.1). The grey clayey silt is increasingly micaceous upwards with the introduction of sand laminae, and has a crumbly texture. It appears to be structureless. No shell layers or plant organic material are present, except for indurated root channels recorded in Log B, between c. 3.010 and 3.260m A.O.D. below the surface of an unconformity.

Laminated clays/silts and sands
(Stratigraphic unit 3)

The grey clayey silt previously described is absent in Log E. The lower silty clay is abruptly and unconformably overlain by c. 1.28m of horizontal and undulatory laminae of fine sand, silts and clays. Structures within this unit are discussed in Chapter 5.2.6.1.

Laminated clays/silts and sands
(Stratigraphic unit 4)

Unconformably overlying the grey clayey silt in Logs A to D is a wedge, c. 0.70m thick, of typical upper tidal-flat alternations of silt, fine sand and clay. The sand, which is buff coloured and usually very fine to fine in grade, forms lenses which are a few millimetres in thickness and of variable lateral persistence. There are occasional pin-stripe laminations. There is a gradual decrease in clay content upwards through this unit. Organic matter is absent, except for patchy indurated root channels at c. 3.255m A.O.D. in Log A, sited below the surface of an unconformity. The large-scale structure of this wedge is discussed in Chapter 5.2.6.1.

Laminated clays/silts and sands
(Stratigraphic unit 5)

This unit was recorded to the north of Log A, and consists of a lithological repeat of the previously-described unit.

Laminated clays, silts and sands
(Stratigraphic unit 6)

Unconformably overlying the clays, silts and sands of stratigraphic unit 4, in Logs A, B and C, is a wedge of similar composition. It is approximately 0.85m thick and consists of undulatory or warped, non-persistent, c. 1 to 2mm thick laminae of silty clay and buff coloured fine sand. Where sand laminae exceed 5mm in thickness, they exhibit evidence of bulbous "micro" loading, evidence either of sudden post-depositional disturbance of the sediment during compaction or of movement of the sediment wedge as a result of sliding and slumping. The wedge is penetrated by modern roots. The sediment surrounding the roots is oxidised forming a "halo" a few millimetres in width. There is no evidence of bioturbation or shell debris.

5.2 ENVIRONMENTAL INTERPRETATION

5.2.1 River Cree: Parkmaclurg borehole

5.2.1.1 Interpretation and conclusions

All eight Parkmaclurg borehole samples were retrieved from the pink-grey clays between 3.20m B.O.D. and 4.95m A.O.D. These samples are now described, from the base of the bore-hole upwards, within the context of changing environmental conditions.

The pink-grey clays, underlying the grey (carse) clays and therefore likely to pre-date the Flandrian transgression, are considered to represent very high tidal mudflats or a low-lying bog, subjected to (? intermittent) tidal influence. It is envisaged that the clays were deposited in boggy, low-lying ground that was widespread in the River Cree and Palnure Burn area. The clays are evident in the Meikle Carse and Muirfad meander sections. Environmental conditions in this area were certainly more terrestrial prior to than during the Flandrian transgression, which transformed the environment into tidal-flats, as represented by the overlying grey clays.

The pink-grey clays exhibit a waning marine/estuarine influ-ence, with a corresponding increase in terrestrial influence up-log. The lowest sample (PMCBH 5), recovered from the base of the borehole at c. 3.20m B.O.D., shows a considerable marine influence since it yielded very abundant unworn shell fragments, together with an unworn but disarticulated Cerastoderma edule valve which was strongly discoloured by iron staining typical of derived material. Bryozoan frag-ments were also evident. Foraminifers and ostracods were common but not identified. The marine component of the sample, therefore, appears to have been derived under storm conditions, shell material being rapidly uncovered from pre-existing beds, but not being transported a great distance prior to deposition, since the shells are relatively unworn. The clay itself is immature. It contains abundant mica, and angular to sub-angular quartz grains, and is likely to be estuarine in origin. The extremely abundant woody debris present in the sample confirms the presence of an estuarine environment and the near proximity of the site of deposition to land.

PMCBH 4, at 2.30 to 2.60m B.O.D., exhibits an extremely diverse marine content, consisting of very abundant fragmented shell material, mostly Cerastoderma edule valves, that exhibit smooth, rounded crenulations and considerable iron staining. The shells are obviously storm-derived as they have been reworked vigorously and repeatedly re-deposited. Sponge spicules, echinoderm spines and bryozoan fragments are also evident. Gastropod columellas (probably those of hydrobids) are present. Foraminifers (mostly Elphidium sp. and Lagena sp.) are present, together with ostracods. The clay is immature, with abundant mica. The energy of the environment was high. Abundant woody debris, together with plentiful seed cases, indicates the closeness of the site of deposition to a terrestrial location.

An increase in environmental energy is evident in PMCBH 7, c. 1.50 to 1.80m B.O.D. Quartz grains are very well-rounded and heavily frosted, and probably came from a marine source. Shell fragments are present. The sediment is more mature than in samples from lower horizons since mica is not so abundant. Plant material is also less abundant. Probably much of it has been washed out, as have been many foraminifers and ostracods, organisms that are present but not as abundant as in samples from lower horizons.

The energy of the environment is reduced in PMCBH 6 between 0.20 and 0.50m B.O.D. The environment is still considered to be estuarine with a marine influence. Shell debris is present, together with sponge spicules and fairly frequent foraminifers and articulated ostracods. Plant debris is abundant.

Summary of the environment between c. 3.20 and 0.20m B.O.D.

All evidence indicates the presence of an estuarine environment (Fig. 5.15), with an initially-strong marine connection or influence. The environment was probably one of migrating tidal mudflats. Energy was constantly fluctuating, as testified by certain elements considered above. The sediment is a typically immature, ill-sorted estuarine one with substantial mica. The diverse macro- and micro-fossil content indicates the marine connection, which gradually wanes up-borehole. There is also, however, a strong terrestrial connection, with abundant wood, plant and seed debris. The site of deposition must be very close to land because vegetational debris is readily eliminated from sediment load during transport.

Above 0.20m B.O.D. there is a distinct change in the environment, reflected in the absence of certain elements. For example, since no ostracods were noted, it is considered that the environment was not conducive to their existence, possibly because of salinity changes. Additionally, the sediment becomes increasingly mature; mica is very rare or absent. The proportion of quartz increases (i.e. the clay becomes sandier), the grains are well-rounded and have undergone considerable attrition, e.g. in PMCBH 1. It is suggested that a loss of sediment supply from a seawards direction is occurring, the same material now being reworked within a restricted area, and therefore becoming increasingly mature. Reworking of material is evident by the presence of elongated "cigar-shaped" and rounded clay/iron concretions. PMCBH 8b (at 0.07m B.O.D. to 0.00m O.D.), formed as a result of

Lithology	Environment	Relative movements of land/sea level
9.20m A.O.D. Dark grey-blue carse clays	Low tidal-flats	Major transgression
4.95m A.O.D.d/c Pink-grey clays	Very high tidal-flats/ low-lying bog (terrestrial)	Apparent regression (loss of marine influence up-borehole)
0m O.D. <u>c</u>. 0.20m B.O.D. Pink-grey clays c. 3.20m B.O.D.	Estuarine - (probably tidal-flats), with strong marine influence	

Fig.5.15 Summary of lithofacies and environments of the Parkmaclurg borehole in relation to eustatic/ isostatic changes (not to scale). d/c disconformity

constant rolling and rounding processes produced by waves in very shallow water. PMCBH 3 (2.80 to 3.00m A.O.D.) contains earthy fragments of vivianite, originally formed under reducing conditions. Oxidised silt nodules (with an iron rim), formed by rolling, have probably been sub-aerially exposed. Restriction of the estuarine environment, as discussed above, is substantiated to a certain degree by the complete loss of shell fragments (and therefore estuarine/marine influence) above 0.21m A.O.D. Furthermore, it is suggested that the environment is now out of reach of most (but not all) tides and is a low-lying boggy area, or very high tidal-flat.

A substantial increase in wood, plant debris and seed cases (PMCBH 8b, 0.07m B.O.D. to 0.00m O.D.; PMCBH 8a, 0.00m O.D. to 0.05m A.O.D.; PMCBH 8, 0.15 to 0.21m A.O.D.; PMCBH 3, 2.80 to 3.00m A.O.D. and PMCBH 1, 3.90 to 4.50m A.O.D.) indicates that the site of deposition is in very close proximity to a terrestrial location. Rare foraminifers are present in PMCBH 8a, 8b, 3 and 3a. In PMCBH 3 and 3a (2.71 to 2.80m A.O.D.) they are likely to have been washed in under storm conditions. Tests are well worn, fragmented and chipped. It is difficult to identify genera and species because of this. Foraminifers are totally absent from PMCBH 2 (at 2.00 to 2.12m A.O.D.) and PMCBH 1 (at 3.90 to 4.50m A.O.D.).

Summary of the environment between 0.20m B.O.D. and 4.95m A.O.D.

It is suggested, on the basis of the afore-mentioned description, that the environment changes between 0.20m B.O.D. and 4.95m A.O.D. There appears to be a loss of estuarine/marine influence. The environment is considered a very restricted estuarine one or to be marginally terrestrial in nature.

The pink-grey clays are considered to be pre-Flandrian transgression (but not necessarily pre-Holocene) in age since, (a) they directly underlie "normal" carse clays, and (b) they represent environmental conditions which were distinctly terrestrial in character and "regressive" in nature.

At 4.95m A.O.D. lies a disconformity between the pink-grey clays and the overlying grey or "carse" clays. The time gap at the disconformity is not established.

Above 4.95m A.O.D. there is a change in lithology to the grey "sticky" carse clays deposited in a lower tidal-flat environment, with a re-establishment of a estuarine/marine connection due to flooding by the Flandrian transgression. The rise of sea-level that produced these marginal marine areas was probably negligible. It takes only a small rise in sea-level to transform a low-lying boggy area into one of low tidal-flats. Detailed timing of events is not considered.

No samples were retrieved from the carse clays of the Parkmaclurg borehole. Discussion of the environment of deposition of the carse clays is best considered elsewhere in this chapter.

Conclusions

The Parkmaclurg borehole sequence exhibits a change in environmental conditions from an initial estuarine setting, influenced by a strong marine connection, to one which becomes progressively restricted, probably near-terrestrial or very high tidal-flats. These relative regressive conditions in pre-Flandrian transgression times were due to the isostatic/eustatic imbalance operating at this time. Isostatic movement (uplift) was marginally outpacing the rise in sea-level that culminated in the succeeding transgression. The regressive conditions were abruptly terminated as the transgression flooded the River Cree estuary area and transformed the low-lying boggy area into an estuarine and lower tidal-flat setting.

5.2.2 River Cree: Meikle Carse section

5.2.2.1 Interpretation and conclusions

A. <u>Meikle Carse section: Logs A to M (locations NX 4432 6265 to NX 4450 6266)</u>

<u>Pale grey clays</u>

Sieved samples (11 in number) were either pale whitish-grey or dark brown in colour, depending upon the proportion of organic content in the sample residue. Mica content varied from nil to slightly common, but generally was low, indicating the maturity of the sediment. No ostracods were recorded and foraminifers (probably washed in) were rare; where present, the latter were too small to identify specifically. Quartz content was generally low, although the percentage of the lithic component of the samples varied as did the lithic composition. Samples MC D sp.8 (1.460 to 1.470m A.O.D.), MC D sp.9 (1.310 to 1.410m A.O.D.), MC D sp.10 (1.160 to 1.260m A.O.D.), MC F sp.10 (0.02 to 1.02m A.O.D.) and MC J sp.6 (1.280 to 1.580m A.O.D.) contained shell material.

Fragmented and whole valve shell remains were most abundant in MC D sp.9 and 10, consisting of whole juvenile to young adult (<u>Cerastoderma edule</u>) forms, exhibiting extensive iron staining of the interior of the valves and heavy erosion of the ribs and umbones, which were smooth. Hydrobid gastropods were also recorded as being common. These were also heavily stained, and the majority were fragmented.

The shelly component of the sample is probably derived from previously deposited consolidated or semi-consolidated gravel material. X

By far the most abundant components of the samples are the wood and grass remains. These vary from common to abundant to very abundant, and constituted very nearly 100% of MC H sp.9. Material varies from very finely-crushed (powdery) grass and wood fragments to twig-sized wood fragments. The twig material is occasionally encrusted with patchy bright blue vivianite. Charcoal fragments were also recorded.

From the previous description (Chapter 5.1.2.2) and discussion, it is suggested that the environment of deposition of the pale grey clays was one of quiet conditions and low energy that received a steady supply of fine clay particles, with the minimum of interruption to sedimentation. Additionally, there is a constant supply of organic material from a terrestrial source in reasonably close proximity. Such environmental conditions would be present in either a boggy marsh environment or on a very high tidal-flat, with minimal, intermittent marine influence.

Dark grey-blue clays

Examination of sieved samples has revealed an abundance of bivalves, gastropods, ostracods and foraminifers, indicative of an established marine affinity, associated with the onset of dark grey-blue clay deposition. Interpretation of certain preserved sedimentary features (described below p. 109) confirms the presence of an estuarine environment.

Evidence of lateral and vertical changes within the lithostratigraphic units is now considered, using evidence collated from laboratory analysis of the samples. A summary of the lithostratigraphic units and corresponding environments is presented in Fig. 5.16.

The dark grey-blue clays were deposited disconformably upon the underlying undulating surface of the pale grey clays. Prior to detailed examination of the sieved samples and sedimentary sequence of dark grey-blue clays, it was possible

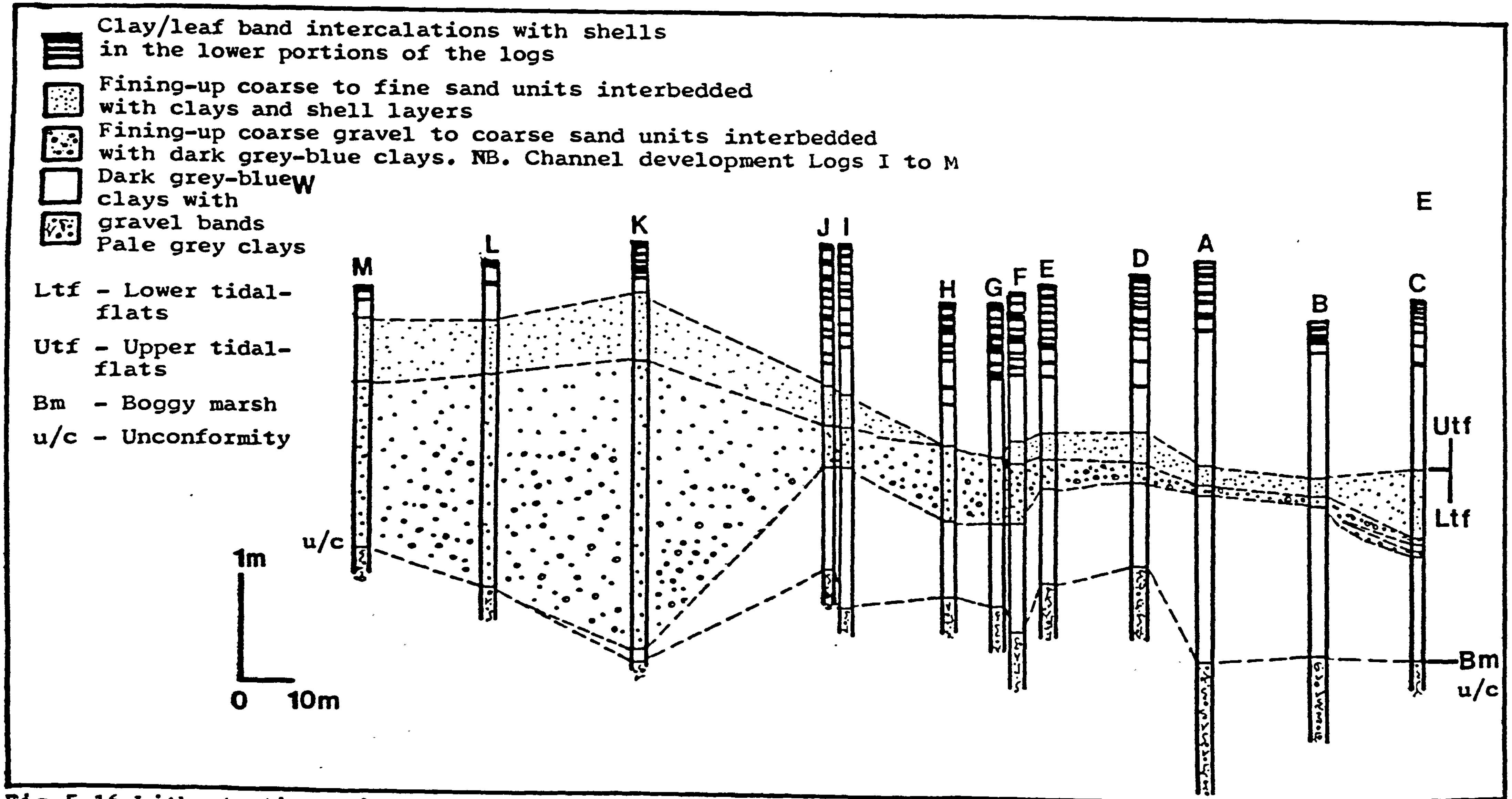


Fig.5.16 Lithostratigraphic summary of units and corresponding environments, Logs A to M, Meikle Carse section

to postulate that the environment of deposition was of a more marine affinity than that of the previously deposited pale grey clays since there is (a) a sudden decrease in vegetation content and (b) a corresponding increase in shell content above the pale grey clay/dark grey-blue clay junction. In the logged profiles A to E, the dark grey-blue clays and interbedded sands and gravels present a fining-upwards sequence. There is a decrease in environmental energy up-log that corresponds with an increase in organic content including that of foraminifers; conversly, organisms decrease in abundance down-log, with increasing grain size. Examined sieved samples MC A sp.12 (at c. 1.40m A.O.D.) to MC A sp.7 (at 2.45 to 2.50m A.O.D.) provide evidence that the energy of the environment was initially high, but diminished up-log. Shell fragments were abundant in MC A sp.12, MC A sp.11 (1.78 to 1.98m A.O.D.), MC A sp.10 (c. 2.03 to 2.05m A.O.D.) and MC A sp.9 (c. 2.15m A.O.D.). They consisted of fragmented and disarticulated but whole valves of Cerastoderma edule which were common throughout. The majority were unstained by iron, although some valves were of a bluish colour and obviously had been derived from older deposits. Whole gastropod shells (chiefly hydrobids) were fairly common, but were also fragmented with a particular bias towards preservation of the robust columellas. Bryozoan fragments and echinoderm spines (confirming the marine affinity of the deposits) were occasional to slightly common. Sponge spicules were also recorded in the basal dark grey-blue clay in MC A sp.12. Foraminifers, fairly common to frequent in MC A sp.10, 9 and MC A sp.8 (2.30 to 2.40m A.O.D.), were probably washed in; the majority are heavily-stained and fragmented. In addition, washed-in fragmented ostracods were recorded in MC A sp.10. No foraminifers were recorded in MC A sp.12, 11 and 7. These are higher-energy deposits. MC A sp.11 was sampled from a semi-consolidated ferruginous gravel band composed chiefly of shells and very abundant quartz grains (heavily stained by an iron cement) and lithic material. The latter is composed of well-rounded fine-grained clasts of mica schist and granite. Fragments of the partially-cemented clasts of MC A sp.11 were incorporated into the clay of MC A sp.10 as a result of storm erosion. MC A sp.10, with an abundant mix of wood and shell material, is interpreted as a storm-deposited layer with derived material of strong marine affinity. MC A sp.7 is a high-energy quartz sand. Cerastoderma edule and Mya sp. fragments are present. Mica was absent or very rare in all samples from MC A sp.12 to sp.7, indicating the extreme maturity of the clays.

The dark grey-blue clays, from their junction with the pale grey clays at c. 2.50m A.O.D., are considered to represent high-energy low tidal-flat conditions (probably migrating), the deposition of mudflats being punctuated by periodic deposition of gravel and coarse sand bands as a result of storm events.

Correspondingly, the environment above c. 2.50m A.O.D. is considered to represent an upper tidal-flat situation. In the sieved residues of MC A sp.6 (at 2.65 to 2.75m A.O.D.) to MC A sp.1 (at 4.150 to 4.250 A.O.D.) plant abundance increases dramatically, being very abundant in general. However, shell debris rapidly becomes rare, diminishing upwards. Foraminifers vary from common to abundant in MC A sp.6 to sp.1. They appear to be more common in the finer clays than in the coarser sands. This may suggest that the foraminifers were in situ. However, a considerable proportion appear to be worn, stained and/or fragmented. This implies that some at least have been transported.

The pattern of distribution and proportion of marine/estuarine/terrestrial components outlined by the samples of MC A is repeated in MC B to MC E. Again, it is possible to distinguish the divide between the lower and upper tidal-flat on the basis of proportions of the constituents in the samples.

Samples MC B sp.11 (1.715m to 1.865m A.O.D.) to MC B sp.8 (2.365 to 2.515m A.O.D.) contain abundant to very abundant (down-log) shell debris comprising a death assemblage of a juvenile/adult mix of Cerastoderma edule and derived, worn and heavily-stained Scrobicularia sp. valves. Again, gastropod shells and columellas are very common to frequent, together with occasional bryozoan fragments. Foraminifers are common to frequent in the clays at MC B sp.11 and MC B sp.8 and possibly are in situ. A continued absence of mica indicates that the clays are consistently mature.

An upward decrease in marine "components" is noted above 2.665m A.O.D. Shell abundance decreases from very abundant to common. Plant remains become very abundant from 3.005 to 3.785m A.O.D. (top of MC B sp.1). Foraminifers are generally very frequent to abundant. Lower-energy upper tidal-flat conditions prevail.

In MC C, sieved samples MC C sp.5 (c. 1.175m A.O.D.), sp.2 (2.535 to 2.635m A.O.D.) and sp.1 (2.935 to 3.035m A.O.D.) indicate lower-energy conditions as compared with the coarser-grained residues of MC C sp.4 (c. 1.735m A.O.D.) and sp.3 (2.335 to 2.385m A.O.D.), which resulted from storm deposition.

Shell debris is rare to occasional in MC C sp.5, 2 and 1; in the latter two samples rare, possibly because the deposits are located above the influence of the highest storm tide. The extremely high abundance of vegetational remains in MC C sp.5 is due to the plants having been washed in (since MC C sp.5 is in a lower tidal-flat setting than MC C sp.2 and sp.1, which are in an upper tidal-flat setting in close proximity to a terrestrial environment). The presence of considerable quantities of mica points to the immaturity of the clays (as compared with MC C sp.4 and 3, where mica is absent). The lithic component of the samples is not as great as that of MC C sp.4 and 3. Ostracods are only occasional in MC C sp.2 and 1, and are absent in MC C sp.5, i.e. they are only present in an upper tidal-flat setting. Foraminifers are frequent in MC C sp.5, 2 and sp.1 but are absent from MC C sp.4 and sp.3. This is a function of grain size and energy; the foraminifers have been washed out of the coarser-grained MC C sp.4 and 3. They may be almost in situ in MC C sp.5, 2 and sp.1.

MC C sp.4 and sp.3, sample residues from a coarse-grade storm deposit, are the complete reverse of MC C sp.5, 2 and sp.1, in that shells are very abundant and vegetational remains are rare to occasional in them. Constituents of MC C sp.4 particularly show definite evidence for the derivation of material from a marine source. The 2+mm fraction was carefully analysed and the following components were recorded. Bivalves were abundant. An equal distribution of unworn right and left valves of disarticulated juvenile Cerastoderma edule indicates their derivation from a nearby source, followed by a short period of transportation to their site of deposition, since they are not sorted. A few examples exhibit worn ribbing and dark blue-black staining. These worn examples possibly were derived from older sediments. An occasional example of Cerastoderma glaucum was also recorded. Other bivalve genera noted were fragmented Venerupis sp. shells, Ostrea sp. valve fragments and remains of piddock shells, bearing spines. It is possible that the last have been derived from a greater distance than the others, since they are typical inhabitants of a rocky coastline. The piddock shell fragments were extensively encrusted by fenestrate bryozoans. Frequent examples of hydrobid gastropods (Hydrobia ulvae and Hydrobia jenkinsi) were recorded. The shell valves were commonly worn at points of weakness such as the suture lines and also had been drilled by boring organisms. The absence of foraminifers and ostracods suggests that either the energy of the environment was too high and the grain size was too coarse for colonisation or the microfossils had been washed out.

Samples representing lower tidal-flat deposits in MC D contained considerable quantities of lithic material. MC D sp.5a (c. 2.310m A.O.D.) was taken from an oxidised (storm) gravel layer, classed as a partially-consolidated, grain- or clast-supported fine-grained conglomerate. Very abundant quartz and lithic grains are cemented along the grain contacts by iron. Occasional grains are observed to be "floating" in an iron-rich clay matrix. The cemented grains are friable upon the application of pressure. Shells (whole and fragmented), also present, are heavily stained. Lithic and shell material continue to be abundant in MC D sp.4 (2.660 to 2.760 A.O.D.) and MC D sp.3 (2.760 to 2.910m A.O.D.). Lithic material is sub-angular to angular throughout and consists of fine mica schists, granitic and fine-grained basic igneous rock fragments. Quartz is sub-rounded to rounded and has been in the "system" for a longer period than the lithic clasts. No foraminifers or ostracods were recorded in the lower tidal-flat deposits. Mica was also absent, as was vegetational debris.

In contrast with the deposits described above, foraminifers were found to be common to frequent in the samples analysed from the upper tidal-flat environment, i.e. in MC D sp.2, 3.110 to 3.210m A.O.D., and MC D sp.1, c. 3.310m A.O.D.; ostracods were recorded in the latter. Mica was also present, and vegetational remains were extremely abundant, consisting of woody twigs, plant stems, grasses and seed cases. The grasses are frequently "matted". Shell material has decreased in abundance but is still fairly common in the upper tidal-flat deposits.

MC E underwent collapse prior to sample collection. Westwards of MC E the lower/upper tidal-flat division is still recognisable (see Fig. 5.16) but rises altitudinally due to the expansion of the lower tidal-flat sequence. Consequently, storm debris of marine affinity is recorded at progressively higher altitudes in logged profiles MC H to MC K. No samples were analysed from MC G because the logged profile collapsed prior to collection. Expansion of the lower tidal-flat sequence is a result of the development of channel-floor and channel - infill deposits, particularly well-developed in MC K where the channel-floor gravels and overlying fining-upwards channel-infill sequence is at its thickest. Evidence of a younger channel at a higher altitude is present in MC L and M, implying that westerly lateral migration has occurred. However, there are problems in establishing the orientation and trend of these channels since there is a lack of sedimentary structures and oriented "clasts" such as twigs. This matter is more fully discussed on page 117. Additionally, instrumental levelling of the logged profiles MC L and M that was found to be inaccurate after the profiles had been destroyed by erosion, casts doubt on the precise altitude of their component strata relative to those in other logged profiles. Positions, therefore, are estimated. Consequently, the position of the channel-floor is only approximate.

Westwards of MC E, the logged profiles display an increasing proportion of thicker interbedded sand and gravel channelled units. There is also an increase in the frequency of erosion surfaces and breaks in the sedimentary sequence. Washed-in twig and leaf concentrations (or lags) occur at the base of the channel units and throughout the upper parts of the sequences from MC F to MC J, these mostly being disoriented but occasionally trending NW to SE. The channel units are infilled by shelly sand or fining-upwards fine gravel to coarse sand. No evidence of cross-bedding was recorded until MC J, where small-scale westerly-dipping cross-beds were recorded at c. 3.080 to 3.130m A.O.D. Individual cross-sets, apparently dipping westwards at c. 20^{o}, were 5mm in thickness. Their bases were "lined" with a closely-packed convex-up lag of juvenile Cerastoderma edule valves. The small-scale cross-beds were erosively truncated above and overlain firstly by a storm shell pocket, followed by 0.05m of ill-sorted medium to coarse sand containing fragmented and whole Cerastoderma edule valves and clay flasers. The base of the flasers (or troughs of ill-defined ripples) were infilled with very finely disseminated grass material and crushed twigs, deposited under a waning and very weak current as the clay came out of suspension. Flasers indicate rapidly-fluctuating environmental energy levels. Ripples stop migrating as the current energy wanes, allowing finer material to be deposited from suspension in the intervening troughs. When energy levels subsequently increase, e.g. due to tidal flood/ebb processes, the ripples migrate once more, "sealing" the troughs. Flasers are very common in a tidal-flat environment. Large-scale low-angle planar cross-stratification in opposing directions was recorded west of MC K and taken to be indicative of the reversal of current directions, hence indicating the tidal nature of the channel setting.

MC K itself exhibits the thickest development of channel-floor and channel-infill deposits. The former are c. 2.50m thick, resting unconformably on the pale grey clay unit. They are composed of fining-upwards, structureless, medium to coarse gravel to coarse sand with variable amounts of disoriented shell material, which is generally more abundant towards the top of the unit deposited on the channel-floor. Shell debris, interlayered with coarse sand at 2.980 to 3.180m A.O.D., at the top of the channel-floor, was recorded as a mounded lag at c. 2.580 to 2.680m A.O.D., where shell valves were closely packed and convex-down. This is not the most stable of positions, and hence indicates rapid "dumping" of the valves under storm conditions. The coarse-grade channel-floor deposits are intercalated in places with patches of dark grey-blue clays.

Above 3.180m A.O.D. the channel-floor is infilled with 0.95m of finer-grade, bright orange, largely structureless, medium to fine sand units. Patchy intercalations of clay exhibit a high carbonaceous content and wood fragments are abundant. Occasionally individual sand units exhibit features that are found only in them, e.g. abundant clay stringers and flasers in some, clay pods, tidal-bedding and twig layers in others. The channel-infill sediment is in turn overlain by 0.45m of leaf, clay and fine sand alternations, probably representing very high tidal-flat or possibly even marsh deposits. These deposits were not fully examined.

Other channel-floor and infill deposits were recorded in MC L and M. Basal coarse gravel (in places pebbly) units, deposited in a channel-floor bar type of setting in a possibly higher channel sequence (see Fig. 5.16), occur in the most westerly logged profiles, MC L and MC M. In MC L, a 0.73m thick cross-bedded unit of fining-upwards very coarse gravel (occasionally pebbly) to very coarse sand was recorded at c. 3.050 to 3.780m A.O.D. The clasts were poorly-sorted and matrix-supported at the base of the unit. Sorting "improved" upwards, clasts being grain-supported at the top of the unit. Individual cross-sets (a few cms thick) were inclined eastwards at approximately 25^{o}. Inclined clay rip-up clasts were also noted within the unit. The unit is overlain by a further 0.02m "pocket" of well-rounded, very coarse gravel rapidly grading to fine sand. It is suggested that this pocket is composed of material reworked from the underlying unit.

It is further suggested that the thicker of the two units was formed in a channel-floor bar-type setting, for the following reasons. The unit is comparable with present-day channel-floor bars of the River Cree, e.g. at Blackstrand (Chapter 10.2.3.1) in that it is fining-upwards, it exhibits unidirectional cross-sets similar in scale (dune size) to those of Blackstrand. Also, it is composed largely of material of a grade similar to that at Blackstrand and the top of the unit (represented by the 0.02m thick pocket) is reworked, as occurs in the bar unit at Blackstrand. However, it is impossible to estimate whether the cross-sets are flood- or ebb-oriented as there is insufficient directional evidence preserved in MC L.

There is development of a clay-nodule lag on the bar surface, followed immediately above by a coarse-to-medium sand channel-infill (c. 0.40m thick), devoid of shell material, but containing twigs and small branches. Clay and fine sand alternations, 0.10 to 0.15m thick, at the top of MC L appear to be upper tidal-flat deposits. The channel-floor bar unit of MC L is traceable westwards to MC M and is at least 0.52m thick, being found at c. 2.660 to 3.180m A.O.D. It may extend a further 0.53 to 2.130m A.O.D.; i.e. the channel is thickening westwards. No planar cross-beds were recorded.

The fining-upwards channel-infill of MC M is similar to that of MC L, but also contains shell lenses, clay concretions and nodules - all washed-in debris.

The coarse gravel, slightly pebbly, channel-bar units of MC L and M were persistent beyond these locations but their observation and recording becomes increasingly difficult due to collapse and slumping of the vertical cliff face. The section was, therefore, abandoned beyond MC M.

The problem of establishing channel orientation and trend is now discussed. It is assumed that the channel deposits of the Meikle Carse section Logs A to M (and particularly MC E to M) belong to the ancient River Cree. However, it is virtually impossible to reconstruct the trend of the main channel (of the River Cree) from the limited directional data (e.g. such as tree branch, trunk and twig material, and cross-set/ripple orientations) gathered whilst recording this part of the section. Data are limited in quantity and quality. Therefore, no statistically sound conclusions can be reached. Planar stratification (cross-beds), where clear, dipped in a general W-E or E-W direction, possibly with a NNW/SSE component, and hence indicating a tidal flow in these general directions. Subsequently, the channel trend would also be in these directions, i.e. parallel to tidal flow. This trend, however, appears to conflict with the cross-sectional shape of the body of the channel between MC I and MC M (Fig. 5.17a & b). The plotting of twig, branch and tree-trunk azimuths proved ineffective. Generally, it is thought that the majority of twig or branch material comes to rest at 90° to the current direction after being rolled along the channel floor. Large tree trunks are more problematical, often forming disoriented log jams providing no clues as to the trend of the channel margins. Individual tree trunks are more likely to be stranded parallel to current direction and therefore parallel to channel margins, but lack of large individual tree trunks within the Meikle Carse section makes it impossible to confirm this suggestion.

When twig and small-branch material of the Meikle Carse section A to M was plotted, the majority of azimuths indicated a NW to SE direction. When this direction is combined with the evidence provided by the cross-sectional shape of the channel (Fig. 5.17a), it is concluded that the twigs must be oriented parallel to current direction and the channel trends NW to SE. If, however, the twigs are oriented at 90° to channel margins and currents (as the majority are in present-day channel environments), the channel would appear to be trending in a NE - SW direction in conflict with the evidence provided by the cross-sectional shape of the channel presented in the recorded cliff face (and in Fig. 5.17b). The problem remains unsolved.

Examination of sieved samples obtained westwards of MC E further reinforced the environmental interpretation already considered. Sample residues from the upper tidal-flat deposits, of MC H (MC H sp.1 to MC H sp.5, i.e. from 2.865 to 3.865m A.O.D.), were interpreted as storm-derived with a

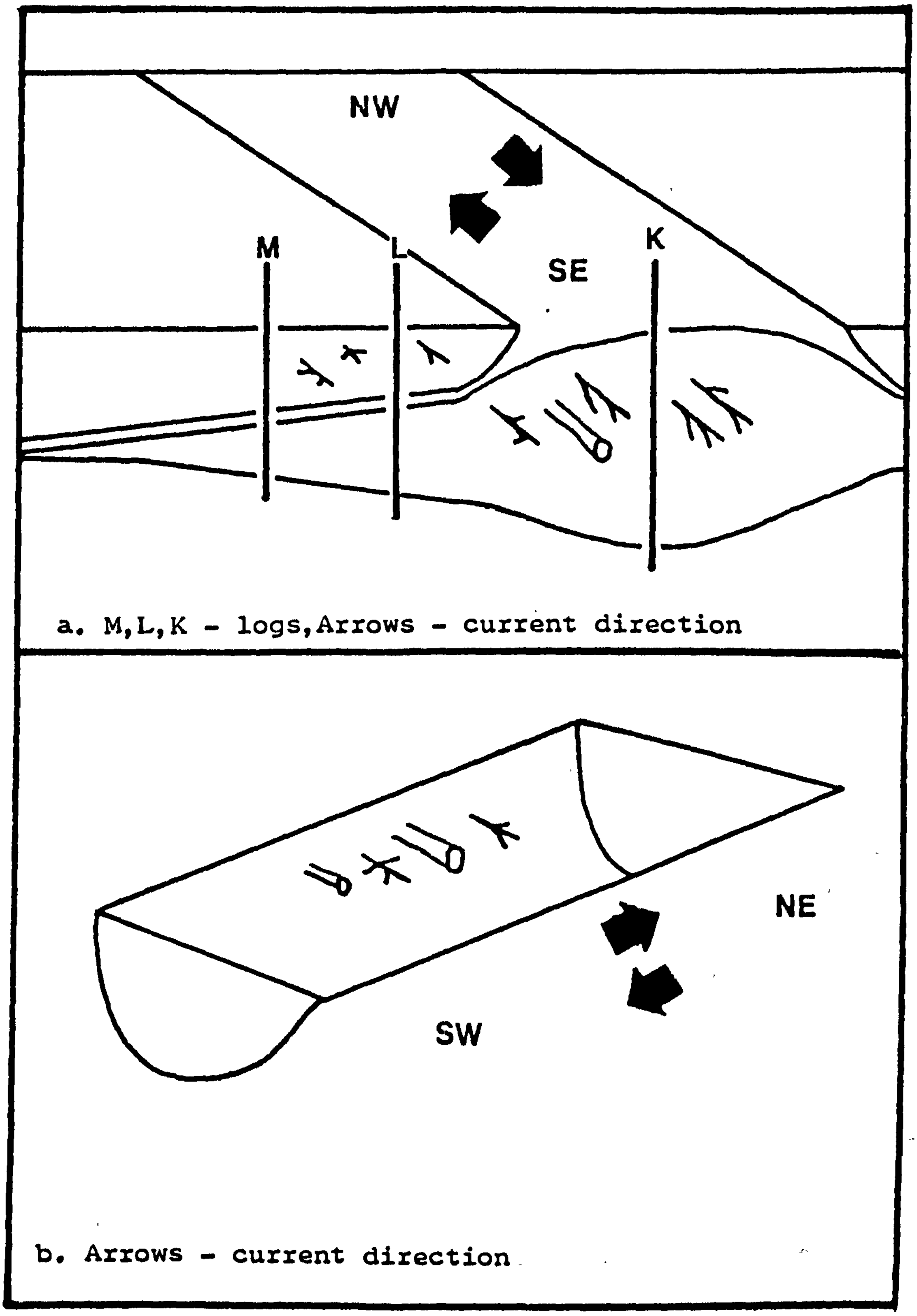


Fig.5.17a Twigs plotted parallel to current flow direction, Meikle Carse section, River Cree
Fig.5.17b Twigs plotted at 90° to current flow direction, Meikle Carse section, River Cree

varied mix of components from marine and terrestrial sources, _e.g._ bryozoan and echinoderm spines fragments, _Cerastoderma edule_ valves and fragments (mixed adults and juveniles) and three species of _Hydrobia_ (abundant), together with frequent fragments of hydrobid columellas, _Corylus_ remains, twigs, bark, seed cases and a few examples of beetle carapaces. _Hydrobia ulvae_, _H. ventrosa_ and _H. jenkinsi_ were all present, the last being most abundant, and indicative of a distinct freshwater component in the samples. Below _c._ 2.765m, the upper tidal-flats grade into more marine lower tidal-flats. There is a decrease in vegetational remains and an increase in the shelly component of the samples. No foraminifers or ostracods were noted. MC H sp.6 at _c._ 2.665m A.O.D., sampled in sand, contained abundant and varied bivalve remains, _e.g._ adult and juvenile _Cerastoderma edule_ valves, _Mytilus edulis_ and _Ostrea_ sp. fragments, (the last encrusted with bryozoa), tellins and two specimens of _Spisula_ sp. In addition, _Hydrobia ventrosa_, _H. jenkinsi_ and _H. ulvae_ were noted, together with echinoderm spines, crustacean claw remains and hazel-nut fragments.

Encrustation of dead bivalves by fan-shaped bryozoan colonies was fairly common, indicating derivation of the organic remains from an area that was kept free of sediment by swift currents, probably marine since bryozoa never inhabit a sandy habitat. Bryozoans were also noted to encrust composite grains of quartz and felspar. The colonies were extremely worn and exhibited restricted growth before the grain concerned was moved on to be re-deposited.

A strong marine element was recorded in MC I sp.4 (3.050 to 3.150m A.O.D.) and MC I sp.5 (2.850 to 3.000m A.O.D.), corresponding to the onset of channel conditions. Shell material, storm-derived from a marine source, is abundant in MC I sp.4. Fragmented and whole valves appear to have been derived from a living colony and a reasonably near source since they consist of both young adults and juveniles; a few of the latter are articulated. Whole hydrobid gastropods were frequent, with a predominance of the species Hydrobia jenkinsi. This was also noted in MC I sp.5. In the latter, juvenile hydrobid shells were extremely abundant but were too small to be identified to species level. Bivalve remains in MC I sp.5 were exclusively Cerastoderma edule, the majority being juvenile to young adult in age. It is concluded that the assemblage was a living one (prior to re-deposition) since there is a heavy bias towards the younger end of the age spectrum. The occasional adult valves appear to be derived; they are smoothed and the ribbing is worn. The assemblage was storm-derived, the colony of young C. edule being disbanded and individuals disarticulated but not carried a great distance to the site of deposition. The shells were probably eroded and dumped within a short distance; older, derived adult shells may have been introduced at this time. The presence of a few articulated valves may point to the closeness of the site of deposition to that where the colony existed.

Although the bivalves are undoubtedly derived from a relatively more marine source than the sediment in which they are included, the presence of the hydrobids points to a strong brackish or freshwater influence. In MC I sp.4 and 5, two-thirds of all hydrobids were Hydrobia jenkinsi, typical of high estuary (less saline than lower estuary) conditions. Other evidence of a "terrestrial" nature includes abundant wood fragments (twigs, bark and charcoal) and Corylus remains.

From the evidence discussed above, it appears that the environmental conditions at c. 2.850 to 3.150 A.O.D. were of a truly estuarine nature, exhibiting a mix of terrestrial and marine elements. Samples from MC I show similar trends to those discussed above.

MC K sp.1 (4.080 to 4.130m A.O.D.) and MC K sp.3 (3.280 to 3.380m A.O.D.) are examples of fine sandy channel-infill deposits with no foraminifer or ostracod remains. MC K sp.6 is a typical storm-derived coarse gravel, traceable to MC L and M and previously discussed and interpreted in terms of environmental conditions.

No samples from MC L and MC M were analysed because of the uncertainty of their exact altitudinal position.

B. Meikle Carse section: Logs N to U (locations NX 4490 6260 to NX 4474 6265)

No samples were examined from this section. Environmental interpretation is based entirely on the changing vertical and lateral relationships of the major lithostratigraphical units described in Chapter 5.1.2.2.

The section MC T to MC R records and traces the development of a prograding (? point-bar) front of an intertidal bank into a channel environment (? palaeo-Palnure Burn) (Fig. 5.18). Slumping of the bar front was followed at a later stage by reworking of adjacent high tidal-flats by the laterally-migrating meander of the Palnure Burn as a result of incision. Further reworking and late-stage infill of the meander led to the development of marshy merse deposits. This sequence of events is summarised and presented in Fig. 5.19.

Dark grey-blue clays - Lithostratigraphic units 1 and 1a

The dark grey-blue clays and interbedded gravels of unit 1 are similar to deposits found at comparable altitudes further west in Logs A to M of the Meikle Carse section. Consequently they are thought to have accumulated in a similar environment, i.e. that of a low tidal-flat subject to periodic storm events (producing gravel sheets). The gravel beds appear to thicken and become coarser in grade eastwards, possibly indications of the existence of a channel-floor or channel environment in an adjacent position.

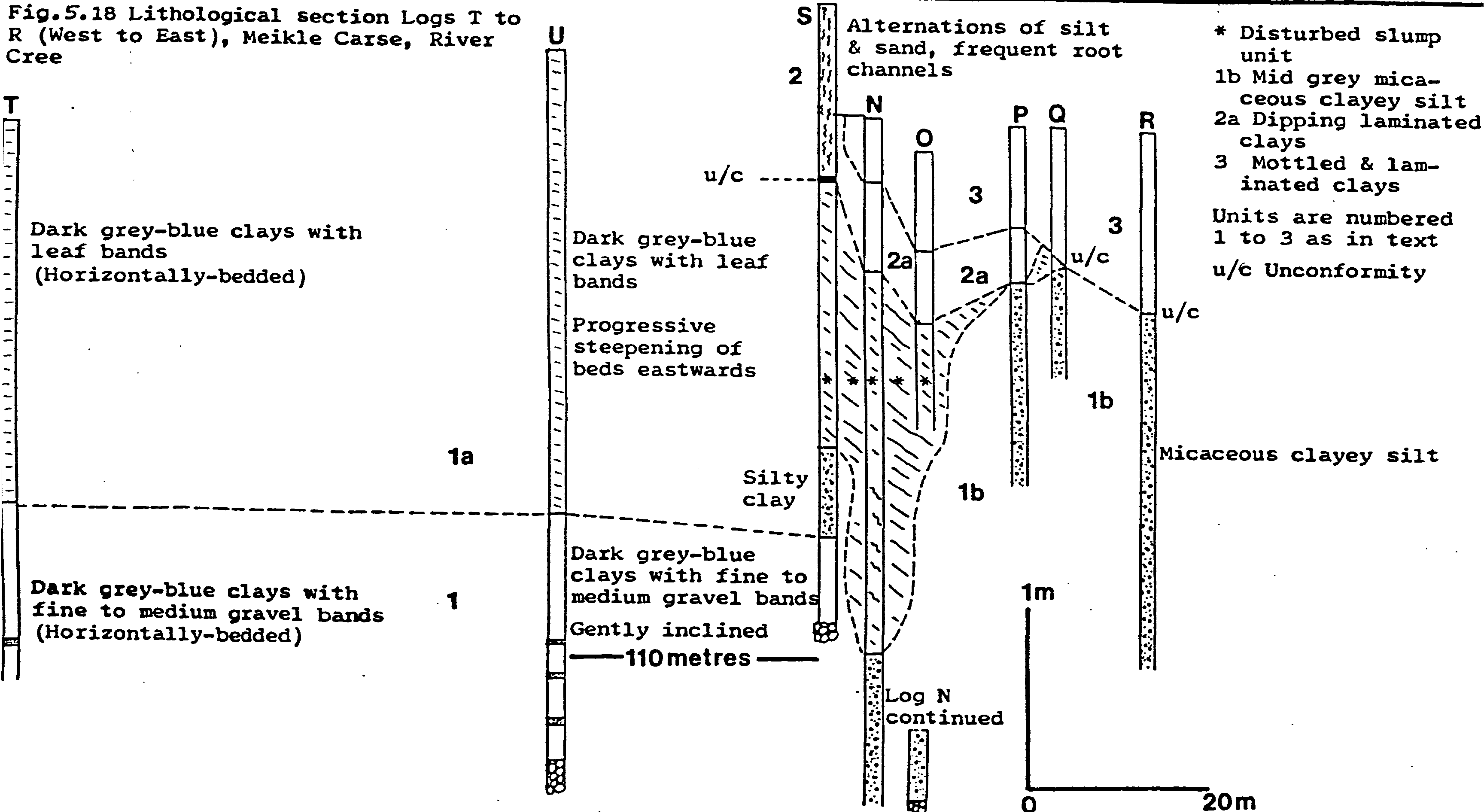
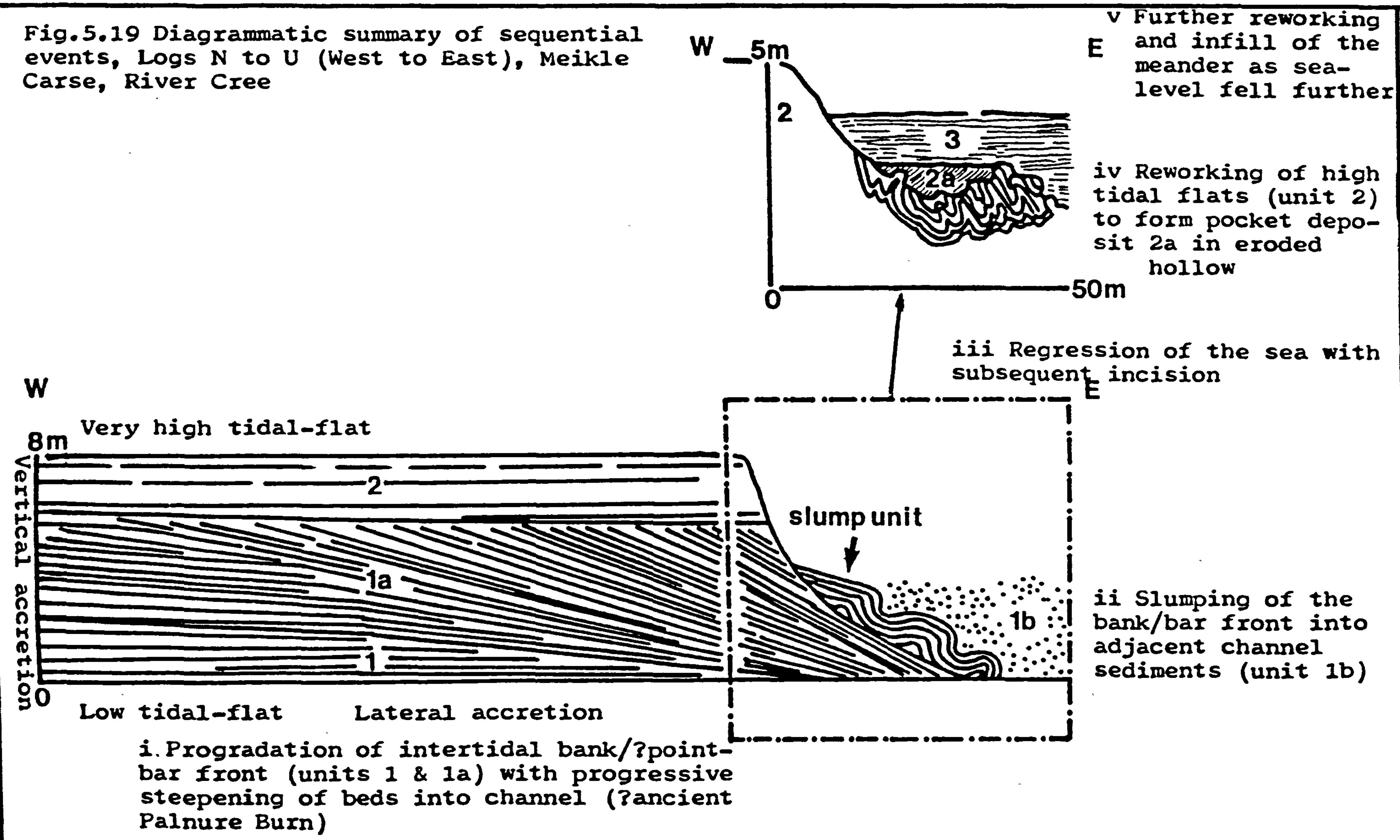


Fig.5.18 Lithological section Logs T to R (West to East), Meikle Carse, River Cree

Fig.5.19 Diagrammatic summary of sequential events, Logs N to U (West to East), Meikle Carse, River Cree



The dark grey-blue clays with leaf bands, which dip progressively more steeply in an E to SE direction along the section (Fig. 5.20), represent a prograding upper tidal-flat, above the influence of storm events (since there is no evidence of the presence of coarse gravel or dead organic, i.e. shell, debris). The prograding front of the upper tidal-flat may have been that of a large-scale point-bar (adjacent to a channel, Fig. 5.20) which would account for the steeply-dipping beds. The latter were subject to instability and slumping, probably as a result of oversteepening and failure of wetted bank sediments. Downslope movement of the still-soft dark grey-blue clays into an adjacent channel has resulted in plastic deformation (i.e. gentle folding and warping) of the leaf bands. Initial failure was by brittle shear. Faulting of the slump was recorded in MC S, but it was impossible to deduce whether base failure was involved or not. The slump occurred into lithostratigraphic unit 1b.

Pale grey micaceous silts - Lithostratigraphic unit 1b

The above unit is believed to represent channel-infill deposits formed contemporaneously with units 1 and 1a (and probably 2) but in a laterally-adjacent environment. It is probable that the deposits pre- and post-date the slump event, although much of the sequence has been removed by later erosive events.

Brownish-grey clay with root channels
Lithostratigraphic unit 2

Upper tidal-flats continued to be deposited and prograded over the point-bar. The flats were formed in a quiet near-terrestrial environment and were progressively stabilised by vegetation.

At a certain stage after formation of the very high tidal-flats, relative sea-level began to fall rapidly and incision and reworking of the deposits by a meander of the encroaching "palaeo" Palnure Burn occurred. Evidence of the preserved meander loop is recorded on aerial photographs and in the

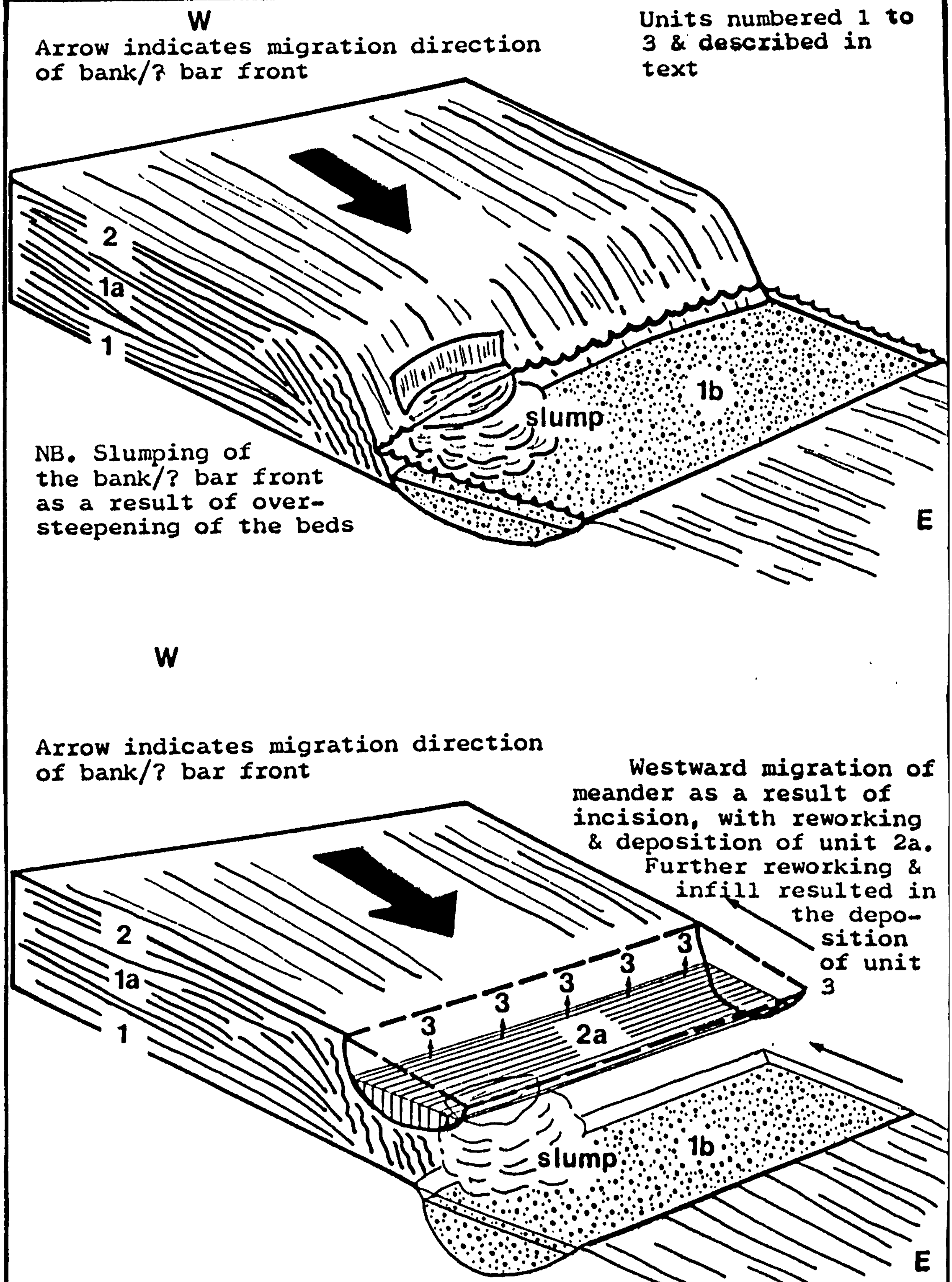


Fig.5.20 Development of palaeoenvironments represented in Logs N to U, Meikle Carse, River Cree

field. The meander-infill (or merse) deposits are further stranded by a period of more recent fall of relative sea-level.

Dipping laminated clays - Lithostratigraphic unit 2a

Reworking of the high tidal-flat deposits has resulted in the formation of a "sediment pocket", deposited unconformably in a shallow hollow that was eroded in the slump surface.

Mottled and laminated clays - Lithostratigraphic unit 3

Further, more extensive reworking and infilling of the meander has resulted in development of unit 3. The mottled and laminated clays appear to be typical marsh deposits, representing the final stage of meander infill.

C. Meikle Carse section: Logs V to Z (locations NX 4409 6270 to NX 4417 6268)

Pale grey clays

The pale grey clays recorded in MC V, and those estimated to occur at depth below MC W, have lithological characteristics similar to the pale grey clays described from elsewhere along the Meikle Carse section and in the Palnure Burn areas, and are therefore thought to have been deposited in a similar environment, i.e. a very high tidal-flat or boggy marsh environment.

Horizontally-bedded dark grey-blue clays with coarse-grade lag deposits

The above unit, resembling others recorded along the Meikle Carse section, is thought to have formed either in a lower tidal-flat environment, with deposition of storm-derived lag deposits in shallow channels, or on the tidal-flat itself. Thicker lag deposits, which occur immediately below the dipping and contorted dark grey-blue clays, originated as basal point-bar deposits.

<u>Dipping and contorted dark grey-blue clays</u>

These are believed to have developed in an upper tidal-flat environment as a result of lateral accretion processes, with accumulation of a point-bar in a general W to E direction. Minor changes in dip direction of "packets" or wedges of sediment, bounded by shallow-dipping disconformities at the surface, indicate changing orientation of the point-bar surface. Eastwards along the point-bar, the point-bar surface progressively dips more steeply; organic layers become "kinked" (Fig. 5.21a) and folded, with subsequent failure and slumping of the point-bar front into an adjacent channel.

A major problem when interpreting the development of a point-bar sequence (and that of the overlying tidal-flat), is one of orientation. It is very difficult to decide a given location's precise position both spatially and altitudinally on the point-bar. At Blackstrand it must be assumed that there was <u>general</u> W to E accretion of a point-bar (that was curved in both plan and profile), accompanied by migration of an adjacent channel (or meander) in a similar direction (Fig. 5.21b). This W to E direction is, of course, indicated by the direction of steepening of the beds. However, locally, due to three dimensional curvature of the point-bar, beds will dip in a fan-like manner, in an array covering all points of the compass. For example, at MC Z the section trended 281^{o} NW to 101^{o} E and the point-bar was dipping S and SE. The direction of migration, therefore, was from NW to SE. Further complications arise, however, due to slumping along the point-bar margin. Movement can be in any direction, depending on the prevailing condition of the surface which, of course, is constantly changing at the margins.

At some stage after the formation of the point-bar, the adjacent channel probably was abandoned and infilled (Fig. 5.21a). The point-bar surface was eroded prior to deposition of a northerly-dipping tidal-flat "wedge" (present

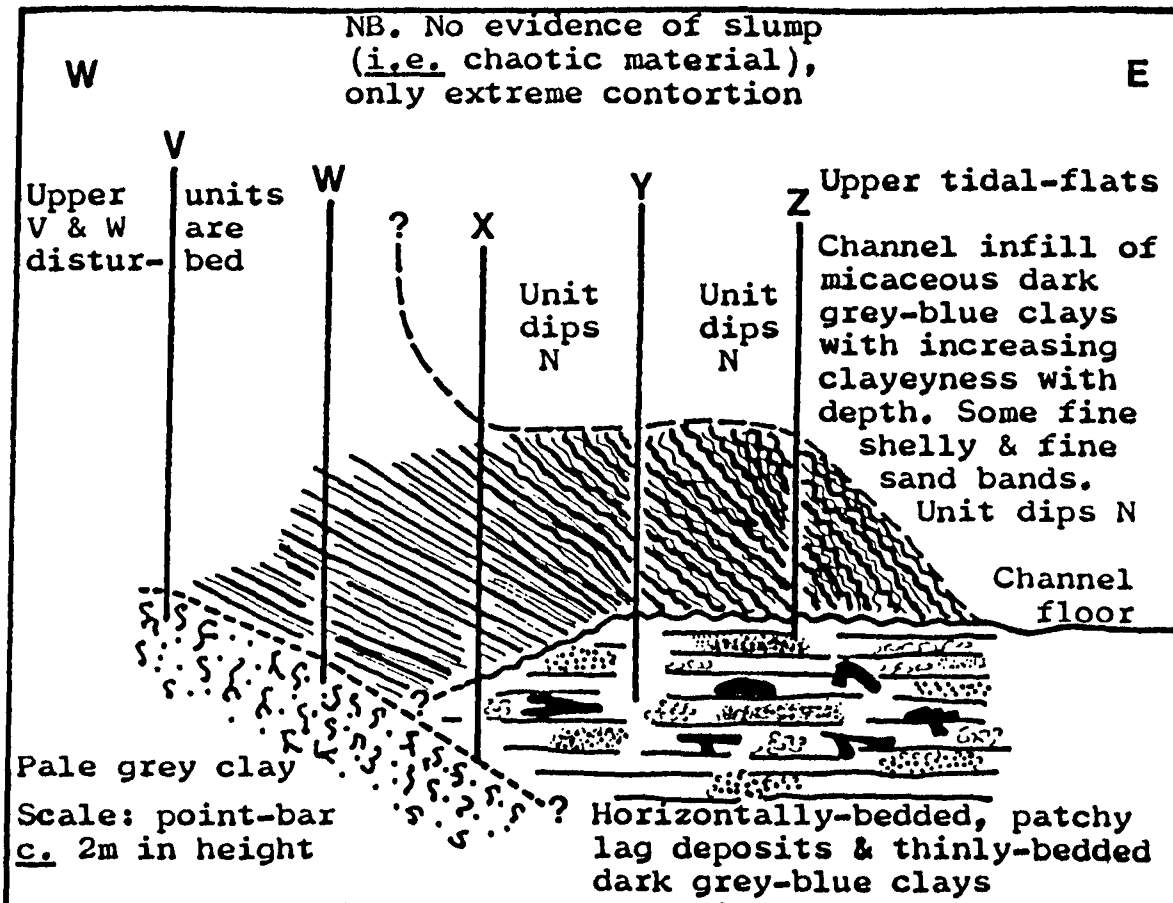


Fig. 5.21a Section to show steepening and contortion of point-bar beds at Blackstrand, Meikle Carse section, River Cree

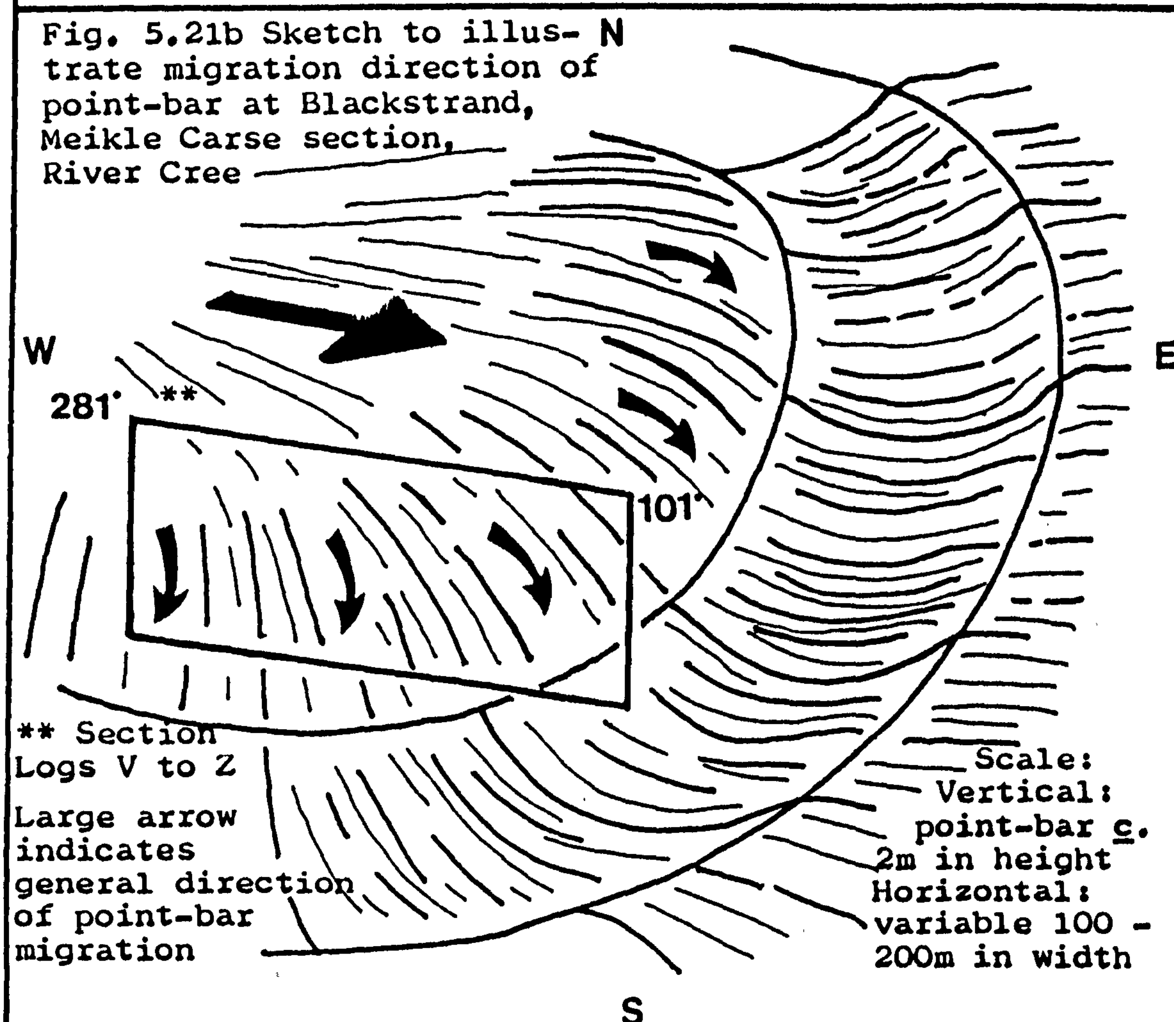


Fig. 5.21b Sketch to illustrate migration direction of point-bar at Blackstrand, Meikle Carse section, River Cree

in MC X, Y and Z).

Disturbed "zone" of dark grey-blue clays, root channels and leaf-band alternations

This unit, present in MC V, W and X, formed in an upper tidal-flat situation. Since there is no evidence of shell debris, the deposits accumulated above the influence of storm events. This unit is especially difficult to interpret. Probably it represents large wedges of disturbed upper tidal-flat, formed as a result of post-depositional movement and adjustment.

The disturbed wedge appears to have been subaerially exposed in MC V where there is a clay crust; possibly it was reworked prior to deposition of merse deposits.

In MC W the wedge is overlain by a faulted-in block of high tidal-flat sediments whose relative position in the sequence is uncertain.

High tidal-flats of MC X, Y and Z

These appear to have formed contemporaneously with the episode of meander channel infilling. Shell debris encountered in MC Z indicates the proximity of the high tidal-flats to a channel which was still marine-influenced despite its infilling.

General conclusions for the Meikle Carse section: Historical Interpretation

Deposition of the pale grey clays in a very high tidal-flat or boggy marsh environment is thought to have occurred prior to the Flandrian marine transgression. The abundance of organic wisps, spots and wood fragments within the clays points to the near-terrestrial character of the environment. With the onset of the Holocene marine transgression at the head of the Cree valley, the area was transformed into that of a lower tidal-flat with deposition of the dark grey-blue clays, initially in hollows and later more generally unconformably on the pale grey clays. The time gap at the unconformity (strictly a disconformity) probably is considerable, but is not known precisely. The dark grey-blue clays accreted vertically and laterally, in the form of a low tidal-flat. They are horizontally-bedded SW of Meikle Carse (section A), forming gravel/shell pavements and shell-only beds of storm origin. Eastwards from this (i.e. between Meikle Carse sections A and B) the beds dip progressively more steeply, indicating the general direction of lateral accretion from west to east. The clays are interbedded with leaf-rich layers of fairly uniform thickness (c. 0.03m) as the tidal-flats were elevated to become upper tidal-flats. No shell material is evident above a certain altitude; presumably the intertidal flat had accreted above the level of the highest storm tide. It has been suggested that the leaf-rich bands may be, in fact, the result of daily accumulation, made possible by the presence of innumerable erosion surfaces between beds of lateral accretion. In effect, therefore, a condensed sequence of lateral accretion is being observed. A continuous supply of leaves in close proximity to the site of deposition and accumulation was certainly available; most leaves are intact and have not been transported a great distance. The area would have been intensely wooded prior to human clearance.

In summary, the sequence SW of Meikle Carse farm passes upwards from lower tidal-flats to high, upper tidal-flats and possibly marsh deposits.

The precise location of the palaeo-River Cree at the time that the dark grey-blue clays were accumulating is unknown. Possibly it was located further west than its present course for a time. It is possible that certain channel deposits within the dark grey-blue clays of section A (Logs K to M) represent the former tidal channel of the River Cree. Channel-floor gravels, pebbles and shell and wood debris are evident. The sequence fines upwards and there is a hint of herringbone cross-stratification (NW to SE orientation), suggesting that the environment of deposition is tidal in nature.

At Meikle Carse section B a major SE-migrating intertidal-bank/point-bar margin exhibits slumping into an adjacent channel (probably the palaeo-channel of the Palnure Burn). The dip of the intertidal-bank/point-bar beds steepens towards the point-bar margin, and the beds become unstable, warped and folded and eventually fall in a slump. The slump at Meikle Carse B is reworked and partially eroded as a result of incision and later migration of a meander of the Palnure Burn. The meander in turn is infilled with a thin development of merse deposits, following a continued rapid regression of the sea from the area. Regression has continued to the present-day.

A similar but much earlier palaeoenvironmental situation of point-bar migration is evident at Meikle Carse section C, at Blackstrand. Unconformably overlying lower tidal-flat deposits, which form a pale grey clay hollow-infill, is an E to SE migrating and laterally-accreting point-bar development in an upper tidal-flat environment. Slumping of the point-bar margin occurred as the beds steepened, with down-slope movement of material into an adjacent channel (occupying the hollow). The channel gradually was abandoned and infilled, and the adjacent point-bar was eroded and younger, unstable high tidal-flats were deposited unconformably above. A channel that was influenced by storm tides (as indicated by the existence of shell debris within it) still persists contemporaneously with the younger high tidal-flat deposits.

5.2.3. Palnure Burn: Magempsy section

5.2.3.1 Interpretation and conclusions

Samples were described and contents analysed (see Appendix p.337). The complete lack of foraminifers and ostracods implies that the environment of deposition was not conducive to their existence. The very small amount of coarse detritus (greater than 75µm, i.e. fine sand) consisted of occasional angular quartz and lithic fragments. These small amounts of coarse-grade material suggest a low-energy environment of deposition. Conversely, clay-grade particles (or aggregates of particles) are highly abundant, varying from powdery in nature in the finer fractions to grain aggregates in the coarser fractions. Rare shell fragments found in two of the samples (Mag S4 and S6, i.e. between 7.285 and 7.745m A.O.D. respectively), result from contamination of the sample material by dirty sieves, but are in fact the only evidence for a remotely-possible connection with a marine environment.

The extremely high abundance of plant detritus, varying in size from fine powdery material to twig fragments, suggests a near-terrestrial environment of deposition. The complete lack of mica from the samples points to the maturity of the clay.

All the above evidence suggests that the clays and organic matter were deposited in a low-energy, near-terrestrial environment at or above the level of high tide and beyond the NTL itself.

The environment envisaged (Fig. 5.22) is that of a muddy inlet reached only by extreme high tides, with deposition of mud from suspension at very low velocities at slack water. The tidal waters appear to have been too weak to re-work the fluvio-glacial terraces on the right bank of the Palnure Burn, i.e. there is no coarse sand in the samples. Therefore, it is possible that the maximum altitude of sea-level at the northern end of the Palnure valley was at the level of contact of the fluvio-glacial and carse deposits. The landward limit of the inlet is placed south of Craignine Bridge, where solid rock is exposed on the river floor; presumably the clays have "feathered out" at this point. The position

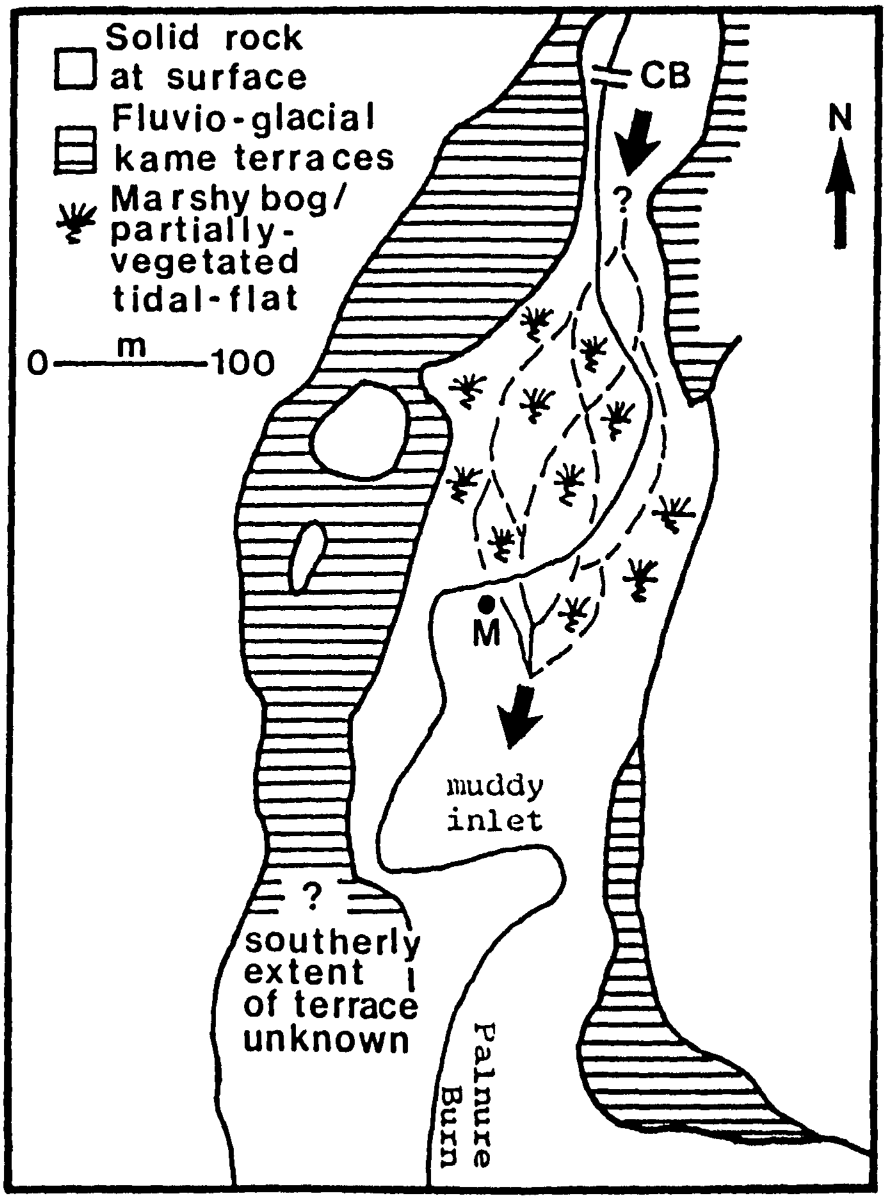


Fig.5.22 Palaeogeography in the vicinity of Magempsy, Palnure Burn c. 5,000 years B.P. CB - Craignine Bridge, M - Magempsy. Thick arrows indicate general flow direction of "palaeo" Palnure Burn through boggy ground. ? - denotes uncertainty of position of Burn as it enters muddy inlet. It is not known if the Burn occupied a single channel or was multi-channelled as shown above

of the Palnure Burn and its point of entry into the muddy inlet is uncertain. No evidence of channel-floor sediment or channel deposits has been found. It is possible that the Palnure Burn merely trickled into very boggy ground, there being standing pools of water that merged into a muddy inlet covered by slack water at high tide. The immediate surrounds of this very sheltered inlet were densely vegetated, sediment being carried in on the tide and being deposited as the water receded, either blown in by the wind or washed in by the Palnure Burn. The prominent plant debris layers, each of which forms a mat, were possibly formed by a rapid fall of leaves that accumulated as a layer on the surface of a standing body of water and were stranded when the water drained away, or more probably were deposited rapidly by a fall of leaves onto an exposed mud surface and covered rapidly by the clay sediment of the succeeding tide.

Conclusions

Magempsy is at or very near to both the lateral and altitudinal limits of the Flandrian marine transgression (i.e. at the chronological end and also at the palaeoenvironmental limit).

5.2.4 Palnure Burn: A75 boreholes

5.2.4.1 Interpretation and conclusions

The carse clays recorded in the section are representative of a high/upper tidal-flat environment, constructed by the processes of migration and lateral accretion by the Palnure Burn, together with vertical accretion, and subjected to periodic storm events/very high tides which are responsible for the deposition of thin shell accumulations.

The mixed gravel and clays in the topmost layers of BH 1, indicate a reworking of the carse clays by the Graddoch and Palnure Burns. The oxidation of the uppermost 2m of the carse clays, resulting in the mottling of the deposits, is a recent phenomenon.

5.2.5 Muirfad meander section

5.2.5.1 Interpretation and conclusions

No samples were examined from this section. Environmental interpretation is based upon differences in facies and their lateral and vertical relationships. The interpretation is further considered within a "historical" context in relation to eustatic and isostatic movements.

A summary of the interpreted palaeoenvironments and their development is given in Fig. 5.23a and b, and now discussed.

The pale grey clays, bearing similar characteristics to the pink-grey clays of the Parkmaclurg borehole and pale grey clays of the Meikle Carse section and occuring at comparable stratigraphic levels, are thought to be high tidal-flat or boggy marsh in origin, and pre-Flandrian-transgression in age. In the Muirfad meander section the environment is further refined to that of a point-bar and associated meander setting (Fig. 5.23a). Although not recorded in great thicknesses in the section, the pale grey clays appear to form a gentle asymmetrical upwarp (see Fig. 5.23a), which has a steeply-dipping western limb and a more gently-dipping eastern limb. The beds are thin or medium in thickness and the "anticline" appears to close in a NW direction. It is suggested that this upwarp may be the remnant of a former point-bar flanked by a meander in an upper tidal-flat setting.

With the onset of the Holocene marine transgression, sea-level rose and the area of upper tidal-flats was flooded and transformed into an expanse of migrating lower tidal-flats cut by meandering tidal-creeks. Considerable erosion removed layers of the upper tidal-flat down to the level of the point-bar and further lowered the crest of the point-bar. The rising sea deposited a patchy lag (of cobbles, peat lenses, shell pockets *etc.*) along the entire length of the

Fig.5.23a Palaeoenvironmental setting prior to the Flandrian transgression

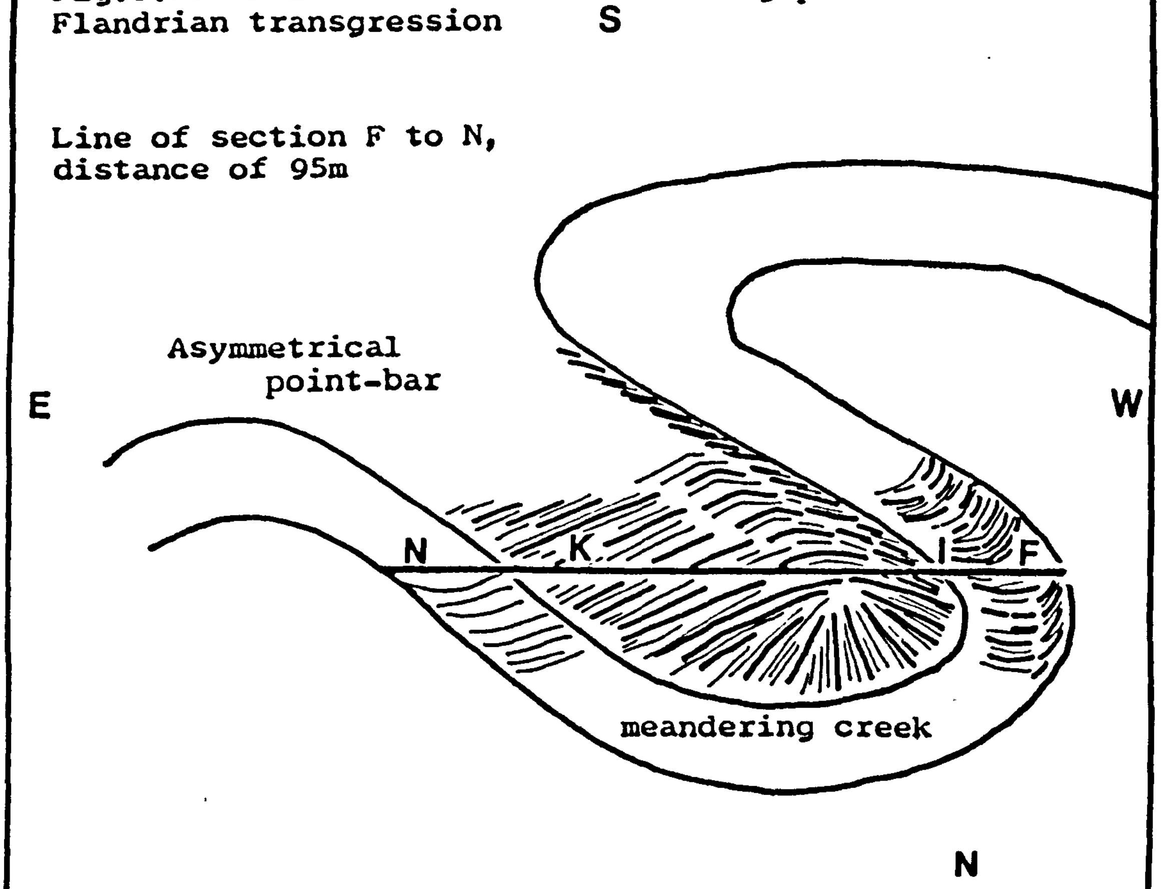
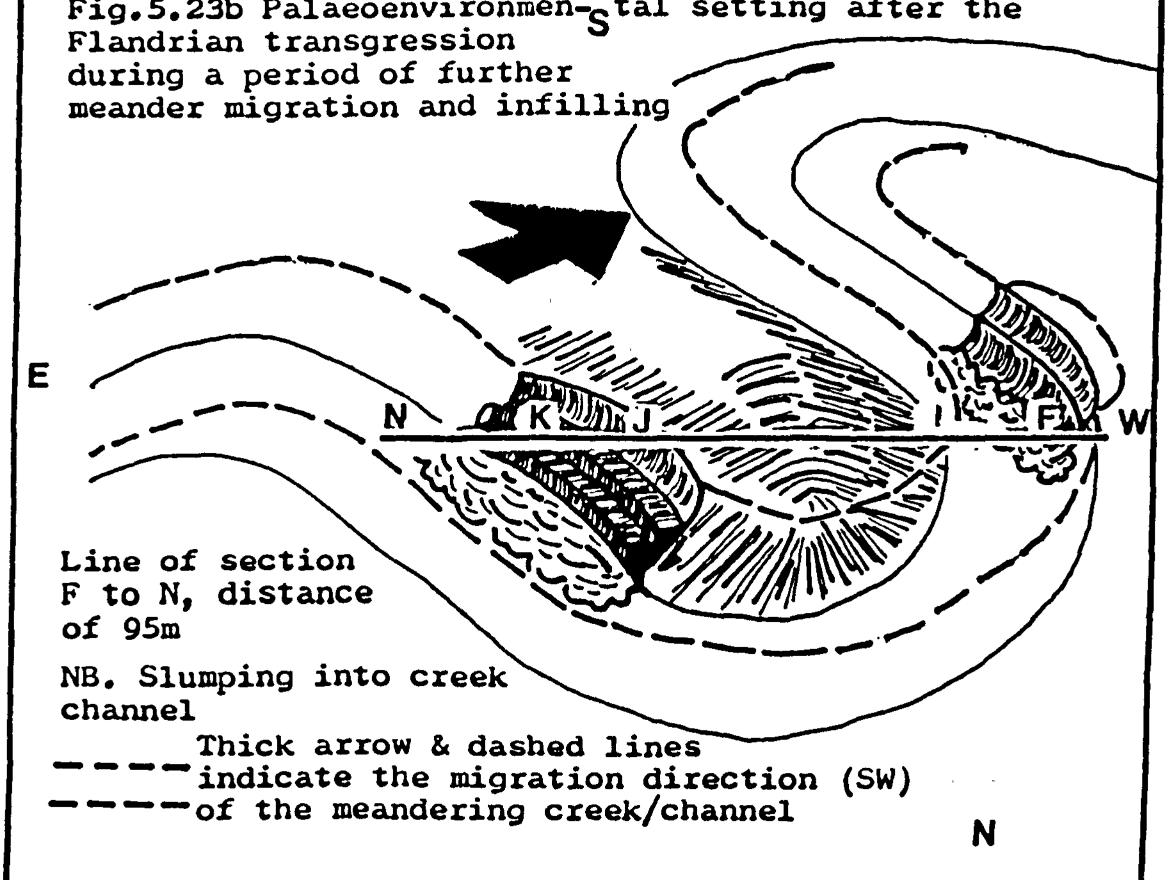


Fig.5.23b Palaeoenvironmental setting after the Flandrian transgression during a period of further meander migration and infilling



pale grey clay/dark grey-blue clay interface, but this lag deposit is particularly abundant in the tidal-channel of the flanking meander. It also appears that in areas where the pale grey clays were softer, i.e. in the tidal-channel of the meander and noticeably from Logs K to N, mud ripples were developed. Their origin and the significance of their orientation are discussed below (page 140).

There followed a phase of deposition of the typical dark grey-blue coloured carse clays on migrating low tidal mud-banks flanked by meandering tidal-channels. In the latter, the clays were interbedded with fine gravel and shell debris and cut-and-fill units, set in the large-scale fining-upwards sequence of a major channel. The sequence of channel deposits of the meander is well-developed between Logs K and N, and to a lesser extent between Logs F and I. In the latter cliff section coarse-grade (pebble) channel-floor bar material is present but on the whole is poorly developed. It is overlain by fining-upwards dark grey-blue clay and fine to coarse sand shell intercalations and lenses which constitute the channel infill.

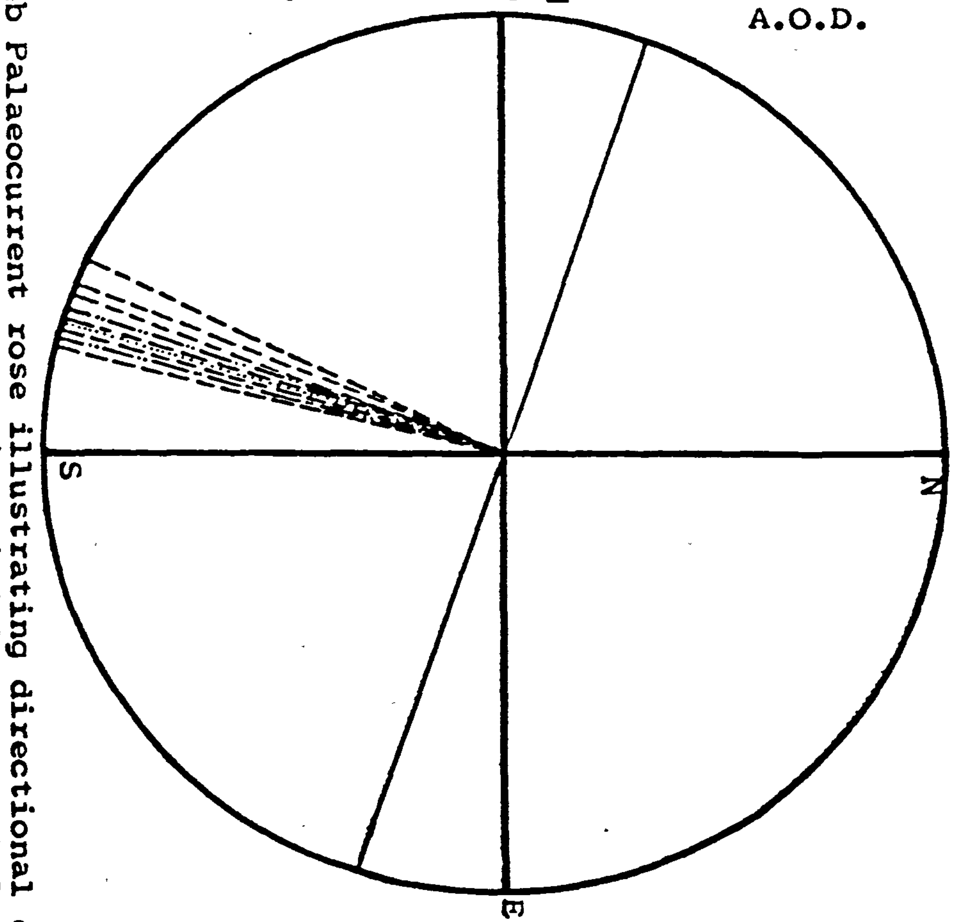
Most of the information regarding the orientation of the point-bar and flanking meandering tidal-channel was obtained by recording and interpreting the orientations of ripple crests at the surface of the pale grey clays and within the dark grey-blue clays, together with one example of herring-bone cross-stratification at Log N. Orientation of branch and twig material was also noted. Data were scarce. All available mud ripple-crest and branch-material orientations, therefore, were recorded and plotted on a rose diagram (Fig. 5.24a and b).

The most reliable evidence of palaeo-current directions and orientation of channel flanks and bank margins is given by the orientation of ripple crests, which trend consistently in the same direction both at the pale grey clay/dark

Fig.5.24a Palaeocurrent rose illustrating directional data (current ripple orientation etc.), Muirfad meander, Palnure Burn

---- Orientation of ripple crests on the pale grey clay surface between Logs K & L at 2.770m A.O.D.

---- Orientation of ripple crests in the dark grey-blue clays between Logs M & N c. 0.84 - 0.89m A.O.D.



.... Orientation of ripple crests at junction of channel/slump deposits, Log G

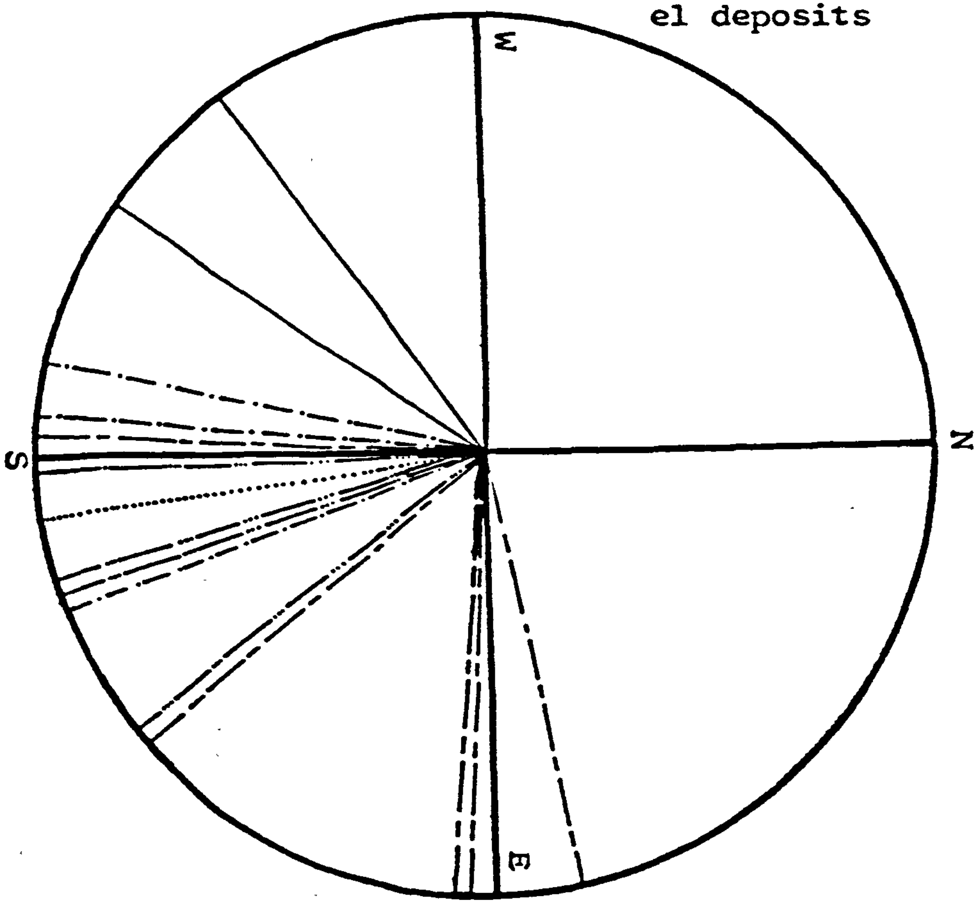
—— Estimated palaeocurrent direction

Fig.5.24b Palaeocurrent rose illustrating directional data (organic material - twigs etc.), Muirfad meander, Palnure Burn (as below)

—— Orientation of twig material, Log M

-.-.- Orientation of branch material, Log N

--- Orientation of branch material immediately east of Log N, base unit, channel deposits



---- Orientation of branch material, E of Log N, middle unit, channel deposits

.... Orientation of branch material, E of Log N, top unit, junction with slump grey-blue clay interface and within the dark grey-blue clays. The ripple crests indicate a WNW to ESE palaeo-current direction and similar trend of the channel flanks, assuming that current flow and the sides of the channel lay at right angles to (longitudinal) crestal orientation. This result corresponds well with the current directions established for the herringbone cross-stratification recorded at the base of Log N (see Fig. 5.24a). The herringbone cross-stratification proves the tidal character of the channel, an inference which is further confirmed by the rounded and slightly flattened nature of the mud ripple-crests.

There appears to be a problem, however, regarding the origin of the mud ripples, since they show no internal structure (i.e. cross-stratification). This may imply that their genesis is related to erosional processes and not to constructional, as originally thought.

Allen (1982, vol. 2, p.259 - 261), quoting the work of several authors, describes structures that he terms "mud ripples", which in size and shape resemble two-dimensional varieties of current ripple which show no internal structure and, forming on a mud bed in response to erosion, lie parallel to current direction. Allen's mud ripples bear a close similarity to those recorded on the Muirfad meander section but, unlike the latter, appear to be strongly asymmetrical in vertical profile.

Allen (1982, vol. 2, p.24 - 28), further considers the development of erosional grooves and ridges in river, and more particularly, tidal environments. Tidal currents locally cut systems of longitudinal grooves and ridges into cohesive beds. However, dimensions of these features described by Allen (p.25), as trending parallel with tidal currents and branching and rejoining "to reach 300m in length, 0.35m in depth and 2m in wavelength", together with those described by Verger (1968) as being "0.1m in depth and 1m in wavelength", are much greater than those of the mud ripples described from the Muirfad meander. The latter have an amplitude of 0.01 to 0.05m from trough to crest, a wavelength of 0.10 to 0.15m and are considered to be small-scale features.

Allen also states that laboratory experiments have shed little light on the origin of erosional grooves and ridges. Under certain flow conditions, weakly cohesive mud beds (as found in the dark grey-blue clays with high water content) are sculptured into longitudinal grooves and ridges which are either meandering or rectilinear. A few of the ripples recorded in the Muirfad section could be classed as "meandering" as they were sinuous in nature. Allen (1969a) has produced "longitudinally meandering grooves" (or rills) experimentally. They are also described by Allen (1982, p.268 - 269), but their dimensions are smaller than those recorded at Muirfad, the intervening ridges varying in width from 0.005 to 0.0075m.

Allen concluded that rectilinear and meandering grooves are the response of a weakly cohesive mud bed to boundary-layer streaks, lying parallel to flow and indicating soft mud bottoms "but are otherwise of uncertain geological significance."

Apart from differences in dimension and structure and their formation having taken place parallel to tidal currents, the mud ripples generated within the dark grey-blue clays of the Muirfad meander are only comparable with those in the literature in that they occur in a tidal setting and are formed in weakly cohesive muds. The suggestion that their orientation is at right angles to current direction appears to be in conflict with the evidence provided by Allen's ripples. It is maintained, however, that the mud ripples were formed at right angles to current direction because, despite a lack of data, all the crestal orientations consistently plotted within a narrow range of direction. However, their mode of formation remains a mystery.

The orientation of branch and twig material (see Fig. 5.24b) does not provide any definite pointer to palaeocurrent direction and in fact, is more unreliable than the information provided by the crestal orientations of the mud ripples. Most of the branch and twig material appears to lie obliquely to the deduced current direction, i.e. between 45° and 90°. It was noted on the present-day Cree estuary that most twigs and branches were rolled along the channel floor at right-angles to current direction at low-current stage, and are found in this position, frequently forming the basal lag of a channel-floor bar or infill. A small component appears to be oriented obliquely (i.e. between 45° and 90°) to current direction. There are also occasional branches oriented parallel to current direction. The above-described situation appears to have existed on the Muirfad meander section.

Whilst the channel deposits were forming, progressively-higher tidal-flats were accumulating on the upper surfaces of the point-bar and flanking environs. Regression of the sea from the area as a result of increased isostatic uplift had been initiated, and the meander (Fig. 5.23b) was now moving in a SW or SSW direction. This lateral migration led to erosion of, and undercutting into, upper tidal-flats by an outer bank at Log F and Logs J to K, producing a well-preserved slump in the last of these logs. The rotational slide (Logs J to K) post-dates the lowest channel-floor deposits because it truncates and contorts them. It was probably preserved by rapid infilling of the flanking channel. The slump between Logs J and K is classified as a "rotational slide" (Hansen in Brunsden & Prior, 1984), a structure which involves shear displacement along a surface that is visible and concave upwards. Failure occurs along a curved, bowl-shaped glide surface. The glide surface flattens downwards, becoming parallel to bedding. Laury (1971) notes that bank failures most likely to be preserved in the stratigraphical record are those produced by large-scale shear failure or rotational slumping. Preservation appears to be most readily accomplished where rotational slumping involves base failure, i.e. where the surface of failure passes below the local thalweg and, therefore, below the depth of active stream scouring (Fig. 5.25). Base failure appears to have occurred at Muirfad meander since still-wet channel-floor muds have been plastically deformed into folds. Areas of active scouring, in which banks are cut in silt- and clay-rich sediments (as in this section, on the outer bank of a former meander), favour the occurrence of deep rotational slumping and possible base failure. Such conditions are common in tidal-flat environments. Fossil displaced-bank sediments, therefore, are rare due to:

1. Restricted environmental conditions in which they can be preserved at best.
2. Low frequency of bank failure within these environments; a point which is invalid on the River Cree estuary and Palnure Burn river at present.
3. A lower frequency of true base failure in these environments.

With regard to the second point, it is suggested that it is due to the high frequency of bank failure on the River Cree and Palnure Burn, both at present and in the past, that the slump is preserved from Logs J to K, since it seems that the greater the incidence of bank failure, the greater the potential for preservation within the stratigraphic pile. In summary, from the above discussion it can be seen that all the necessary environmental causes were present for the formation and preservation of a rotational slump.

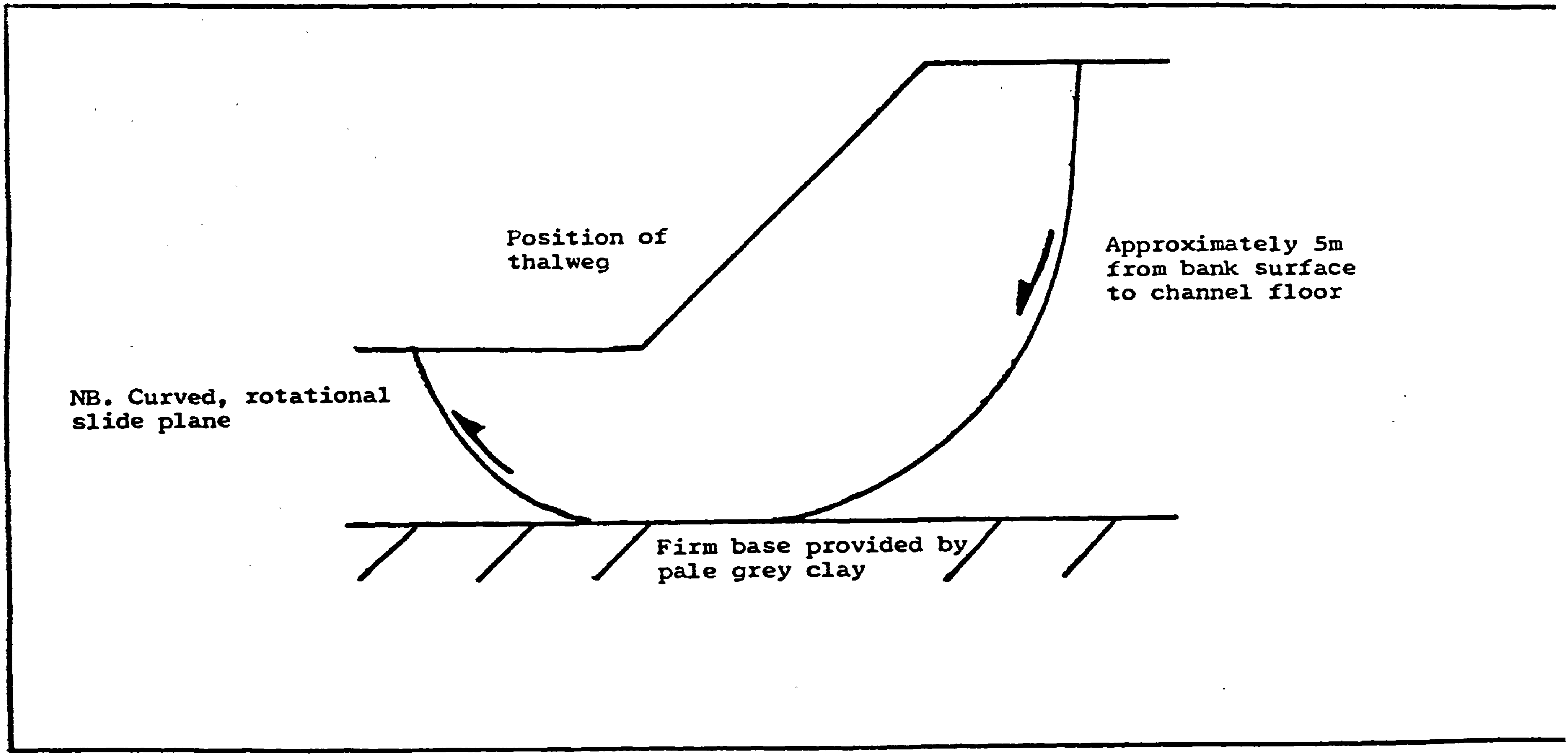


Fig.5.25 Diagram illustrating bank failure above a firm clay base

The action of a diurnal tide upon the near-vertical, incised (outer) banks of the River Cree at Meikle Carse and strongly-meandering Palnure Burn at Muirfad meander causes intensive scour during the high-water stage, leading to over-steepening of the banks. This induces failure of wetted sediments along rotational slump-surfaces during the low-water stage. This mechanism of failure is frequently enhanced during periods of inclement weather.

The River Cree at Meikle Carse is c. 150m wide, and its outer bank is c. 5m in height (Fig. 5.26a). Three large-scale (c. 30+m wide and c. 20m in length) rotational slumps have formed as a result of undercutting processes. The slumps have possibly been affected by base failure. The lower areas of the rotational slumps at the base of the channel flank are quickly draped by a covering of loose watery mud in the course of successive deposition by tides. This may aid the preservation of the slumped material, which normally would be eroded. It is suggested that the preservation potential of the slumps at Meikle Carse is particularly low, chiefly because of the extremely erosive nature of the tidal action at this location, and because the river is "open" in cross-section and has a bed-load of sandy sediment which may aid in the erosion of the slumps.

On the Palnure Burn, at Muirfad meander, however, the slumps appear to be disproportionately wide and long in relation to the channel (Fig. 5.26b), being c. 20m in width and c. 15 - 20m in length, whilst the channel width is only c. 5m at low-water stage. Bank height is the same as on the River Cree. It is suggested that the slumps at Muirfad have a greater preservation potential than those on the River Cree at Meikle Carse because the erosive power (although tidal) of the Palnure Burn is not as great as that on the River Cree, and therefore cannot modify the slump and erase it. Additionally, the Palnure Burn has no significant coarse-grade bed-load to aid erosion at this location.

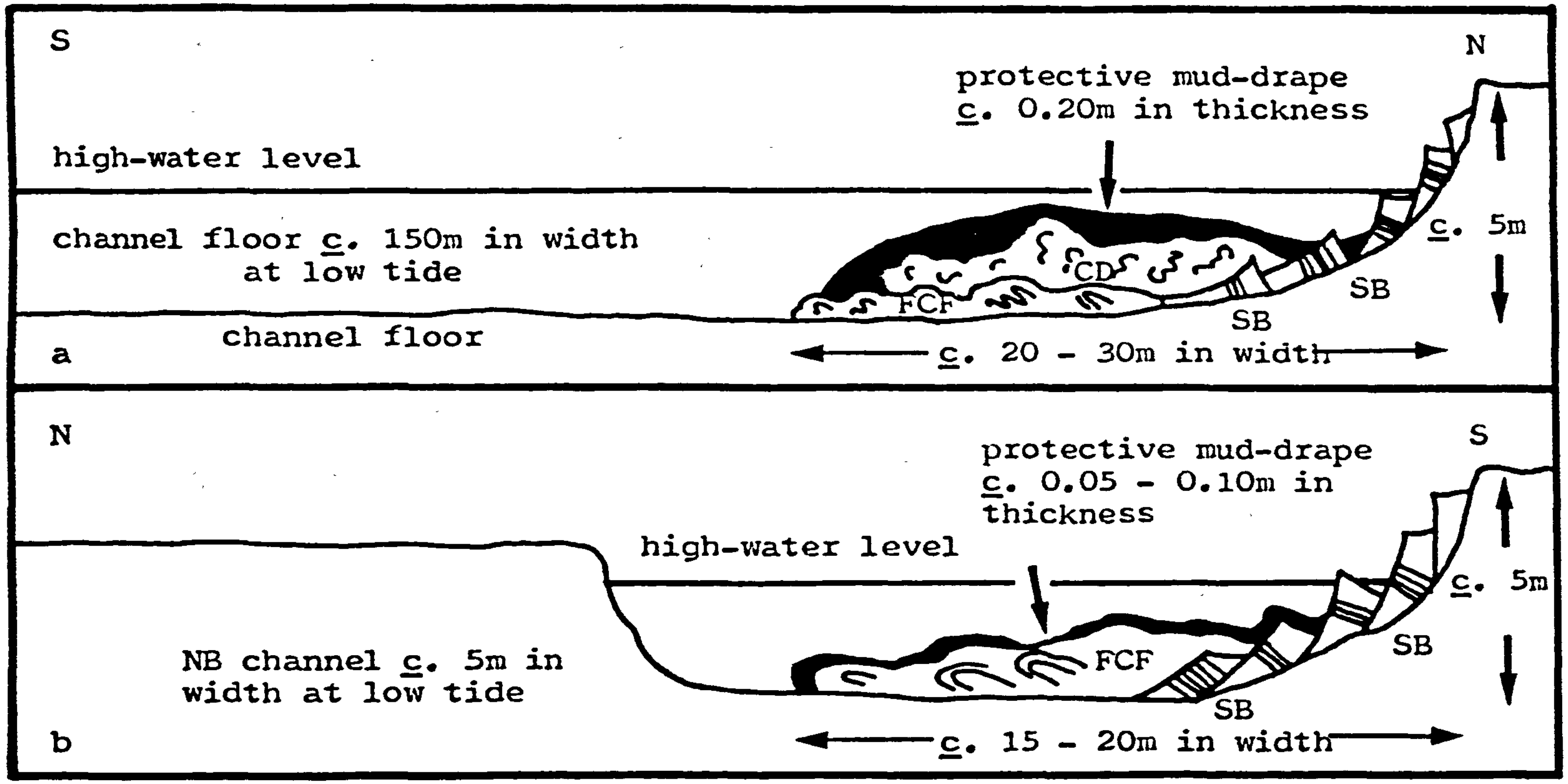


Fig.5.26a Large-scale rotational slump, River Cree, Meikle Carse. NB Chaotic debris (CD) immediately below mud-drape underlain by folded channel-floor (FCF) deposits. SB - Slide blocks
Fig.5.26b Large-scale rotational slump, Palnure Burn, Muirfad meander. NB Folded channel-floor deposits and slide blocks

The former meander between Logs J, K and N and F and I, of the Muirfad meander section, was rapidly infilled as it moved SW or SSW. High, sandy to marsh tidal-flat conditions were established "blanketing" the underlying "topography". The deposits of fine sand were subject to the effects of post-depositional settling and compaction, apparently to a greater extent over the channel areas, possibly due to differential compaction of the coarser-grade sands and gravels that underlay these areas.

Conclusions

The cliff section at the present-day Muirfad meander reveals a section through a much older point-bar meander that has remained "hidden" until incision by the present-day Palnure Burn. No evidence of the presence of this particular point-bar and accompanying meander appear on aerial photographs of the area, although there is ample evidence of former meander scars in the vicinity. Exact orientation of the preserved features is difficult to ascertain because of a general lack of directional data (absence of features such as ripples *etc.*).

5.2.6 Palnure Burn: Long Loop section

5.2.6.1 Interpretation and conclusions

No samples were examined from this section. Environmental interpretation is based upon changes in lithology and the closely corresponding stratigraphy.

A summary of lithological and stratigraphical units, together with elements of structure, is shown in Fig. 5.27. Environmental interpretation of the stratigraphical units numbered 1 to 6 is now considered.

Stratigraphic unit 1 - The dark grey-blue clays, and 1a coarse gravel pebble unit

The dark grey-blue clays were deposited in an actively migrating lower tidal-flat channel-floor environment.

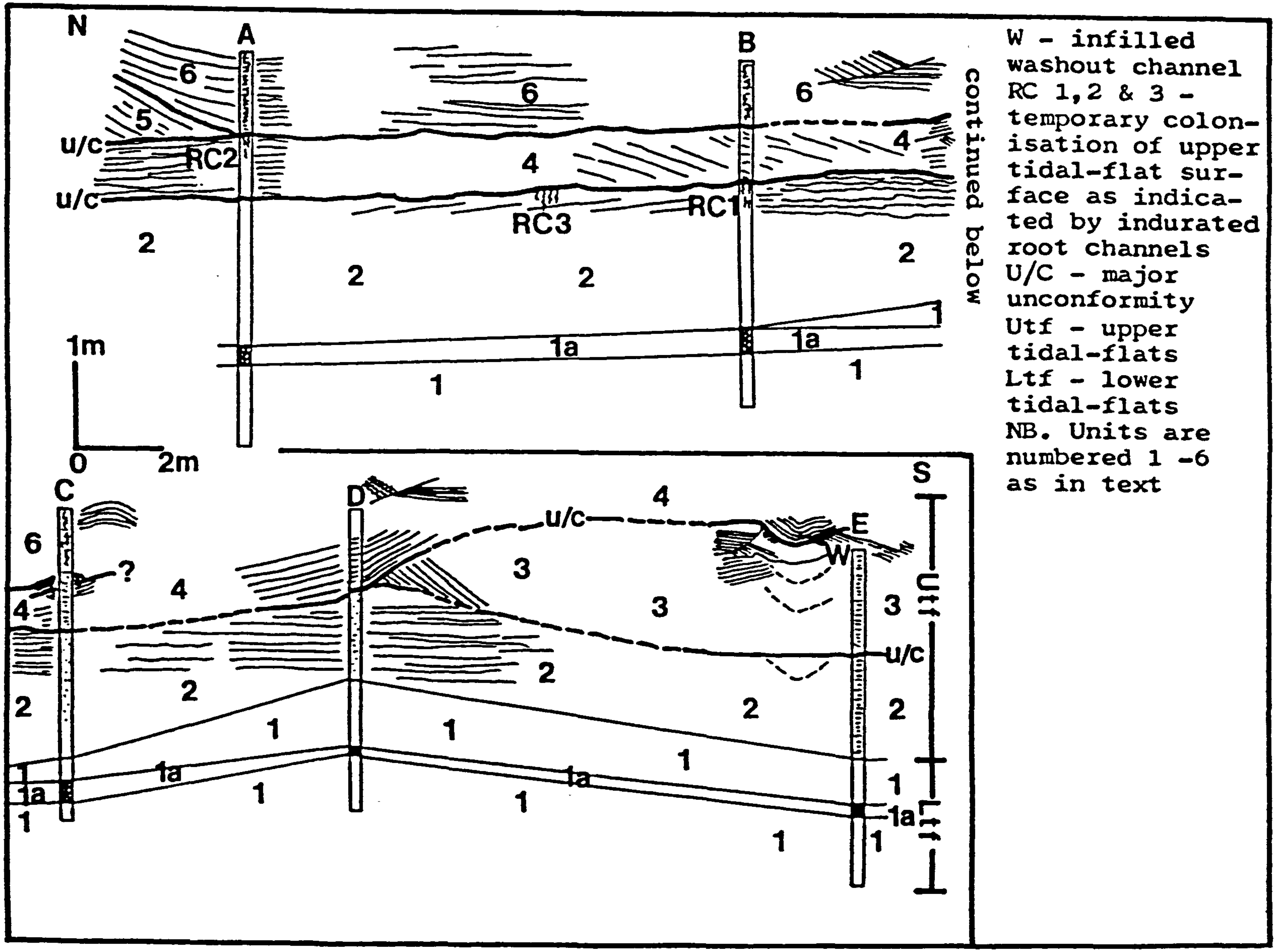


Fig.5.27 North to south lithostratigraphic section (Logs A to E), Palnure Burn

Horizontally-deposited bands of convex-up shell valves are storm-derived in origin, plucked from a living community but not transported a great distance to their site of deposition, since they are unworn. Richter (1922) noted that, in flowing water, 80 - 90% of disarticulated valves are arranged convex-side up, i.e. in a hydrodynamically stable position. This explains why, in the vast majority of bands within the dark grey-blue clays, shells are arranged in this manner, since they were deposited under fast flowing water (storm) conditions as the lower tidal-flats were migrating. Energy of the environment is high. A thick channel-floor lag deposit (stratigraphic unit 1a) is present, consisting of ill-sorted and therefore storm-deposited or dumped cobbles, pebbles and coarse gravel. However, fining upwards of the unit occurs in Log B. After an initial "dumping" of pebbles, cobbles, shells and branch material by a fast current, the latter waned rapidly but steadily. NE - SW oriented branch material apparently was too heavy to be incorporated into the fast current and was rolled along the channel floor. Typical lag debris such as twigs, leaves and pockets of transported shell debris are also present. Shell bands are relatively few above the channel-floor gravel and pebble unit.

The lower tidal-flats and channel unit are overlain unconformably by prograding upper tidal-flats of stratigraphic unit 2.

Stratigraphic unit 2 - Grey silty clay to grey clayey silt

The above unit, representing upper tidal-flats, rests unconformably on lower tidal-flat deposits in Logs C, D and E and because of erosion, rests directly upon channel-floor material in Logs A and B. It is thought that the unit represents deposition on a lower point-bar situation in an upper tidal-flat environment because:

1. In the upper part of stratigraphic unit 2, beds in the vertical face of the section around Log D are dipping steeply westwards (out of the face) towards the present-day Palnure Burn. At Log C the dip is less steep, c. 35°, and has rotated to a NW direction. North of Log B, the dip has further decreased to 5 - 10°, and is directed to the NNW. It is suggested that such a rotation and decrease of the dip inclination would occur on a point-bar. It is probable that the lower point-bar was accumulating and prograding in a NW or NNW direction by "wrapping" itself around an initial "high", produced by the presence of the lower tidal-flats between Logs D and E.

2. The presence of vertical clusters of indurated root channels at RC 1 (Log B) and RC 3 (north of Log B) immediately below the unconformity and truncated by it, indicates that vegetation (probably reeds) colonised the original surface of deposition. This has repeatedly occurred (see stratigraphic unit 4), due to successive stages in accretion of the point-bar. Colonisation by reeds would occur on the point-bar surface. The reeds would later be destroyed by further deposition as the point-bar underwent accretion and NW or NNW progradation. Furthermore, vertical roots cut through dipping undulatory, in addition to horizontal, laminae. Each major unconformity recorded lies above the original surface of deposition on the point-bar.

<u>Stratigraphic units 3 to 6</u>

These units are considered to represent unstable "wedges" bounded by gently NW-dipping upper point-bar deposits in an upper tidal-flat environment. Most of the evidence of disturbance (<u>i.e.</u> faulting, slumping and sliding) occurs towards the southern end of the section which is located stratigraphically lower in the upper point-bar and is more prone to instability than the overlying younger wedges. Additionally, stratigraphic units 3 and 4 (at Log C) are deposited directly on the more steeply-dipping parts of stratigraphic unit 2 and are, therefore, more prone to faulting and instability. In addition, underlying stratigraphic unit 2 at this position are the dark grey-blue clays which contain a high percentage of fluid, again contributing to the instability of the overlying point-bar deposits.

Stratigraphic unit 3 - Laminated clays, silts and sands

This unit, present only between Logs D and E, rests abruptly on silty clay in Log E. Features such as herringbone cross-stratification, miniature washouts and infill (of rills?) indicate the high energy of this upper point-bar situation. High-angled dips of bedding, south of Log D, may be the result of slumping. Post-depositional failure of the deposits, resulting in small-scale faulting along a rotational slip surface (c. 0.30m in length), is evident north of Log E. It appears that this wedge of sediment is highly unstable.

Stratigraphic unit 4 - Laminated clays, silts and sands

This unit is present from Logs A to D. Extensive erosion of the upper point-bar deposits occurred after deposition of stratigraphic unit 3. Draping of the fault at Log D occurred as new sediment was deposited. North of Log C, beds appear to dip gently in the same direction as the unconformity. Small-scale post-depositional thrust faulting (fault c. 0.60m in length) is evident at Log D. Patchy colonisation of the point-bar surface by vegetation was recorded in Log A.

Stratigraphic unit 5 - Laminated clays, silts and sands

This unit is present to the north of Log A, and is bounded by two surfaces of unconformity and the end of a wedge whose direction of deposition is not known.

<u>Stratigraphic unit 6 - Laminated clays, silts and sands</u>

The uppermost-recorded upper point-bar unit (present in Logs A to C) is relatively stable, with only minor evidence of post-depositional movement of sediment, probably as a result of compaction in the form of micro-loading. The laminae are warped, and thereby provide additional evidence of sediment compaction and settling of the point-bar sequence.

<u>Conclusions</u>

The sequence described and interpreted at Long Loop on the Palnure Burn represents northwestward and north-northwestward accretion and accumulation of a large point-bar in an upper tidal-flat setting, and progradation of the point-bar over older channel-floor and lower tidal-flat deposits. Sediments of the point-bar are arranged into "wedges" or "packets", bounded by large-scale NW-dipping unconformities. Variable orientations of the units can be accounted for as follows:

(a) The point-bar being large in scale, deposition was occurring on an inclined surface that probably was also undulatory as a result of irregularities in current flow.

(b) Point-bar deposits are prone to instability, with frequent slumping and sliding due to rapid removal and deposition of material in a high energy environment.

(c) Some faulting and movement was produced by post-depositional compaction and settling.

CHAPTER 6 - HISTORICAL AND PALAEOGEOGRAPHICAL RECONSTRUCTION OF THE UPPER CREE ESTUARY AREA IN RELATION TO SEA-LEVEL CHANGE

The sedimentary and stratigraphic sequences of the upper Cree estuary are summarised in Figure 6.1.

The historical development of the sequences and associated environments within the context of sea-level change in the upper Cree estuary is now discussed in detail, and is summarised by a series of sections and palaeogeographical maps.

During late-Glacial times and very early in the Holocene Epoch the upper Cree estuary area was a low-lying boggy environment (Fig. 6.2a and 6.2b). The area was marginal-marine in character. The margins of the upper Cree estuary area were flanked by extensive fluvio-glacial outwash terraces (Fig. 6.2a), deposited as a result of ice ablation. The central valley of the River Cree was probably a mud-filled boggy depression, occasionally influenced by marine waters, either at the tidal limit or reached only infrequently by the highest storm tides. The exact position of the palaeo-Cree is uncertain, but the river flowed in a NW to SE direction and may have been braided as probably was the N- to S-flowing Palnure Burn.

Generally, the area was a stagnant marshy bog in which accumulated fine-grained deposits (pale grey clays of sequences 1 to 3, Fig. 6.1) and abundant transported material such as leaves, nuts and twigs, and peat cobbles. The vegetational component of the deposit indicates that vegetation had re-established itself on a bare land surface (Fig. 6.2b). The glacially-determined limits of the central boggy area, not defined exactly (see Fig. 6.2a), probably extended seawards, merging with lower tidal-flats and lagoonal and marine facies recorded by the B.G.S. in Wigtown Bay. The position of the late-Glacial shoreline (Fig. 6.2a) is also uncertain.

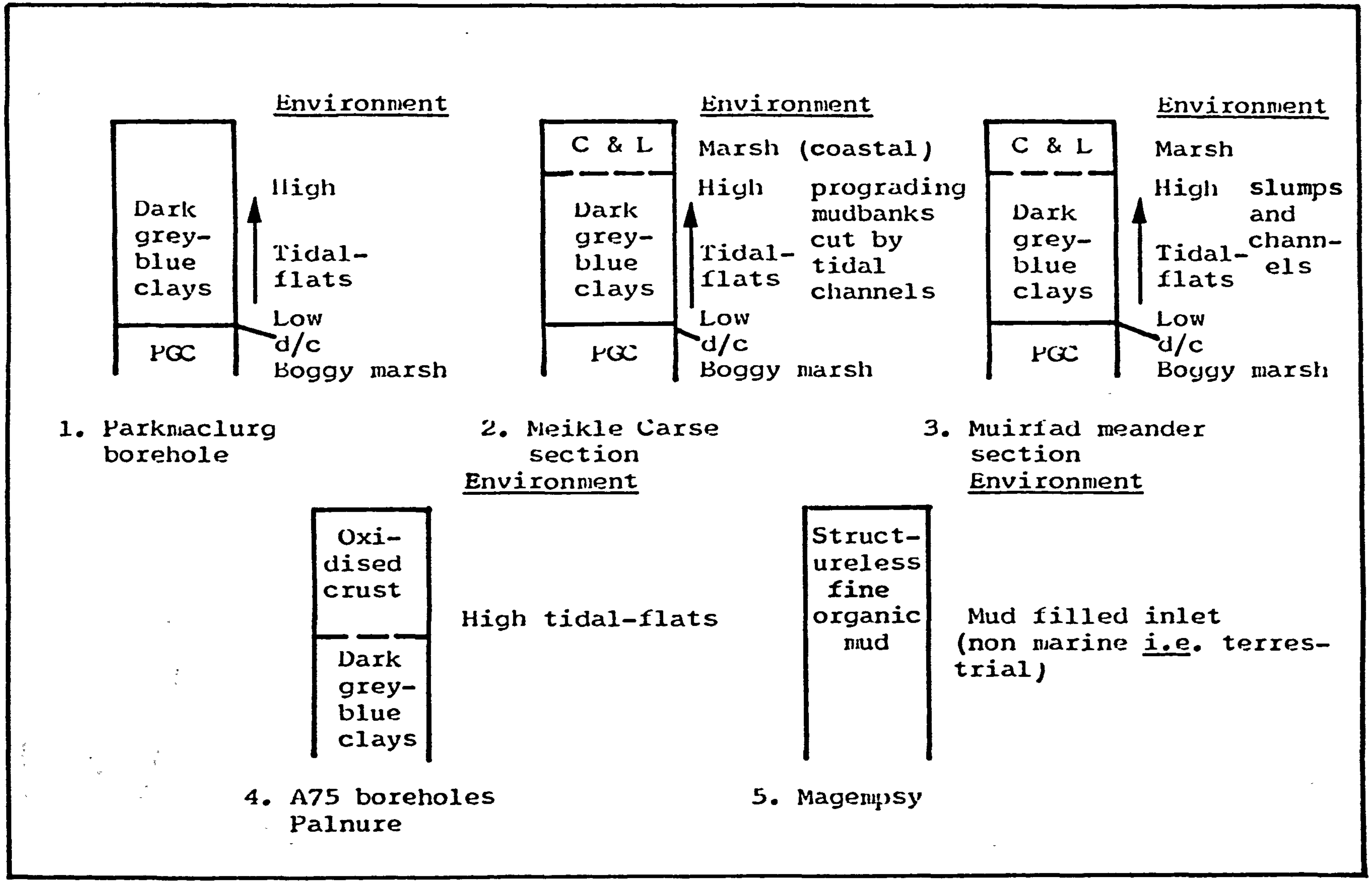


Fig.6.1 Summary sequences for the upper Cree estuary area. C & L - Clay and leaf layers, PGC - Pale grey clays, d/c - disconformity

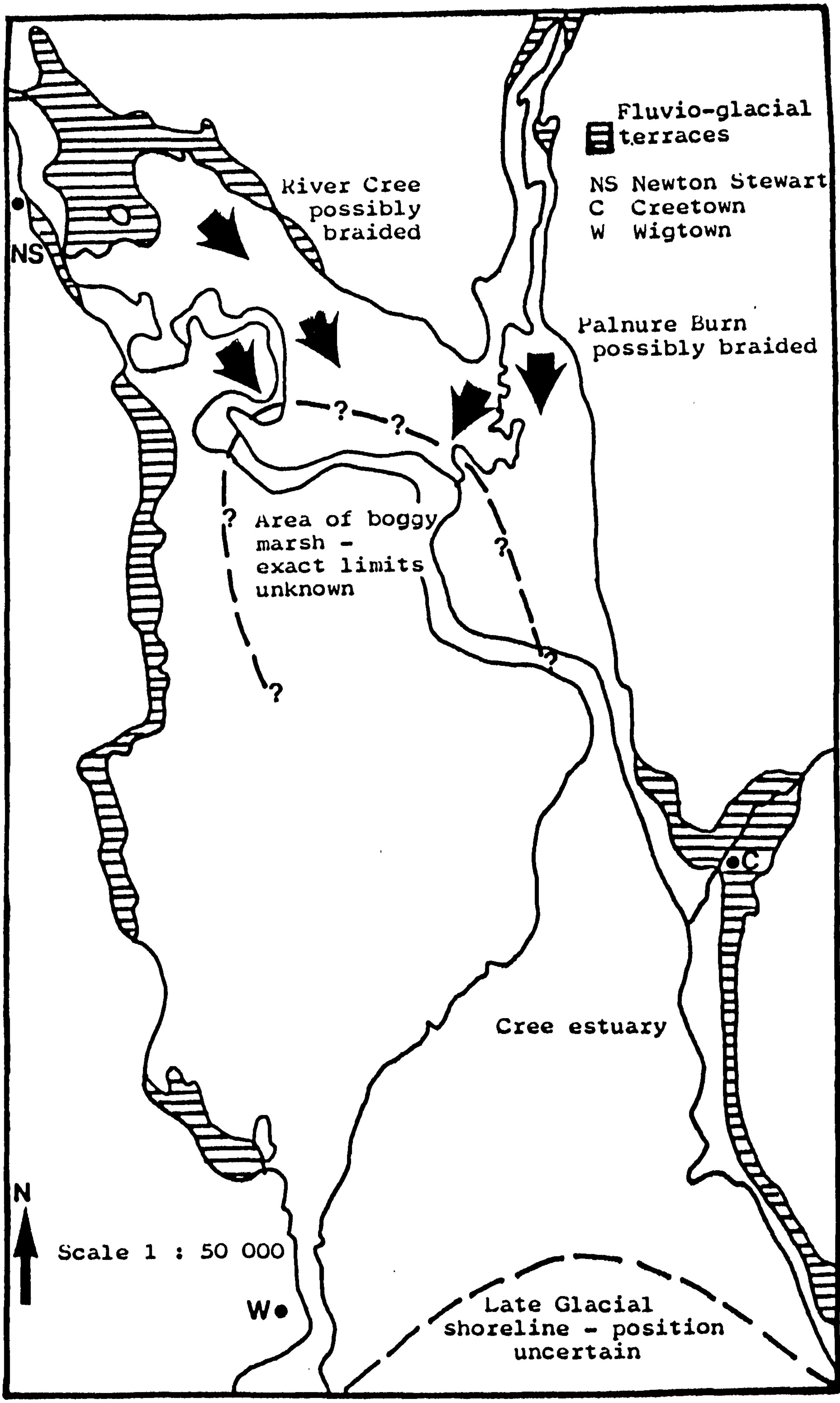


Fig.6.2a Palaeogeography of the Upper Cree estuary area, late Glacial to very early Holocene times

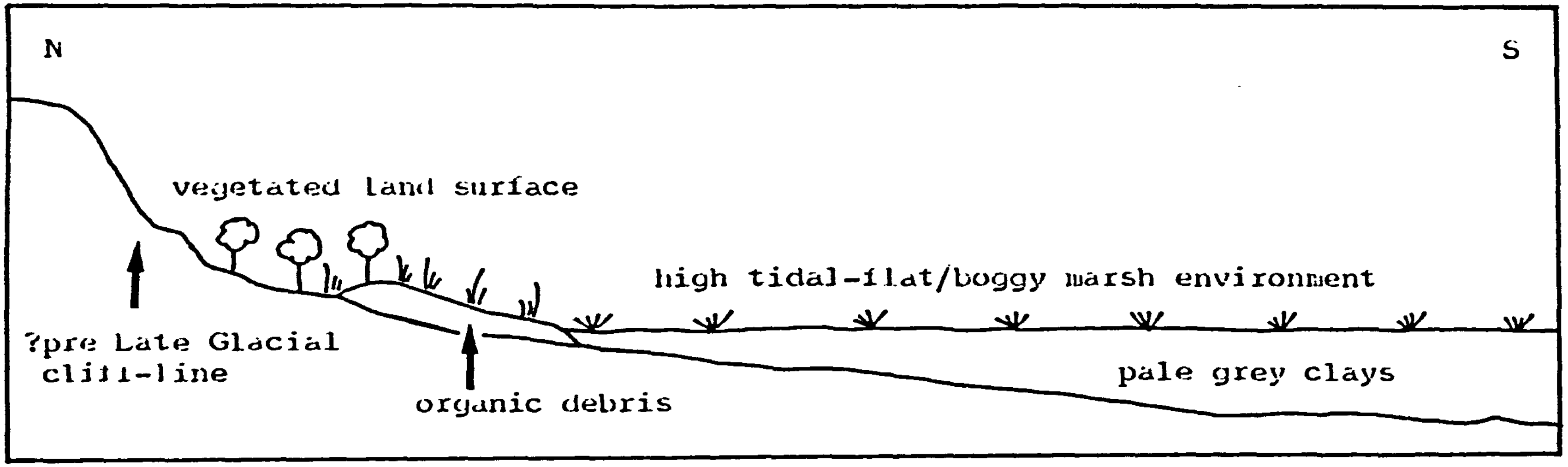


Fig.6.2b North to south section from Palnure to the Cree estuary at Meikle Carse during the late Glacial to very early Holocene times. NB Scale N to S approximately 1.5 km

The marine waters of the Holocene marine transgression gradually flooded northward from Wigtown Bay, penetrating the upper Cree estuary c. 7,900 years B.P. (Fig. 6.3a). Some time after this the sea penetrated the valley of Palnure Burn. As the marine waters encroached landwards, eradication of all previously-existing environments in the lower Cree estuary area and Wigtown Bay occurred. In the upper Cree estuary the pale grey clays were eroded and the margins of the fluvio-glacial outwash terraces were reworked to varying extent, giving rise to transgressional lag material. At the maximum of the Holocene transgression, the marine waters reached the (late-Glacial) cliff base in the vicinity of Palnure (Fig. 6.3b). However, this situation did not prevail for a long length of time.

There is a distinct disconformity between the pale grey clays and dark grey-blue clays (see sequences 1 to 3, Fig. 6.1), the latter definitely being more marine in character as a result of the proximity of marine (tidally influenced) channels. In a W to E direction from Parkmaclurg through Meikle Carse to the mouth of the Palnure Burn (Fig. 6.4a, p.160 and 6.4b, p.159 , situation c. 6,480 ± 107 years B.P.), the area was transformed into extensive low to high tidal-flats and mud-banks which accumulated by processes of lateral migration of channels and accretion of varying size. Positions of the creeks are not easily established. By c. 6,480 ± 107 years B.P. local regression had been initiated (cf. Jardine 1975, pp. 184-185) and seaward progradation of high upper tidal-flats and marsh had started (Fig. 6.4b). Commencement of peat formation due to growth of a local coastal marsh occurred at Palnure. This environmental situation remained as described above up until c. 5,000 years B.P.

From c. 5,000 years B.P. to the present-day there was a gradual change from marine to brackish to freshwater conditions (Fig. 6.5a and 6.5b). The creeks continued to be infilled and contract. Traces of small creeks are observed on aerial photographs and are easily recognised because they were

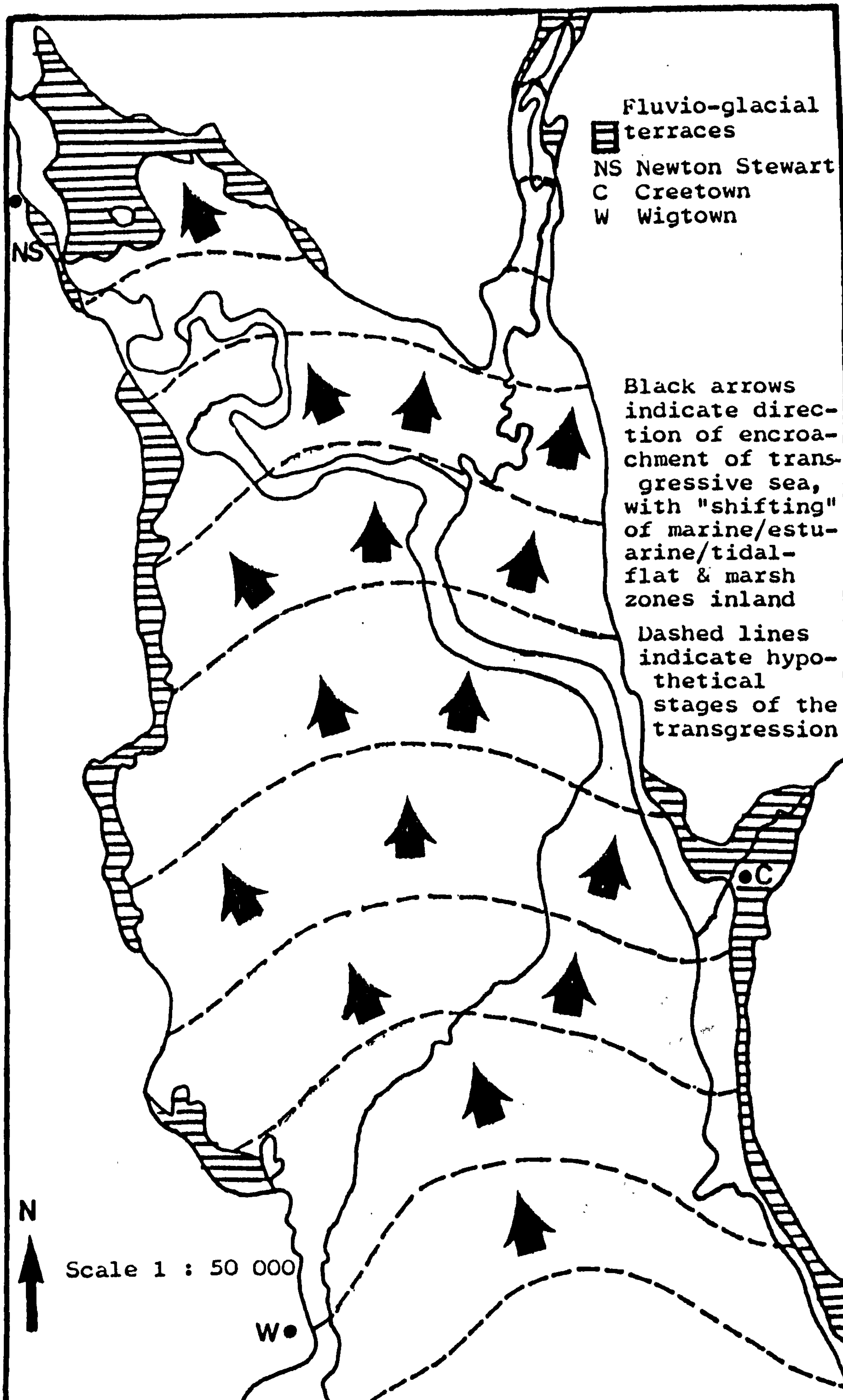


Fig.6.3a Palaeogeography of the Upper Cree estuary area, pre 7,900 years B.P. to 7,200 years B.P.

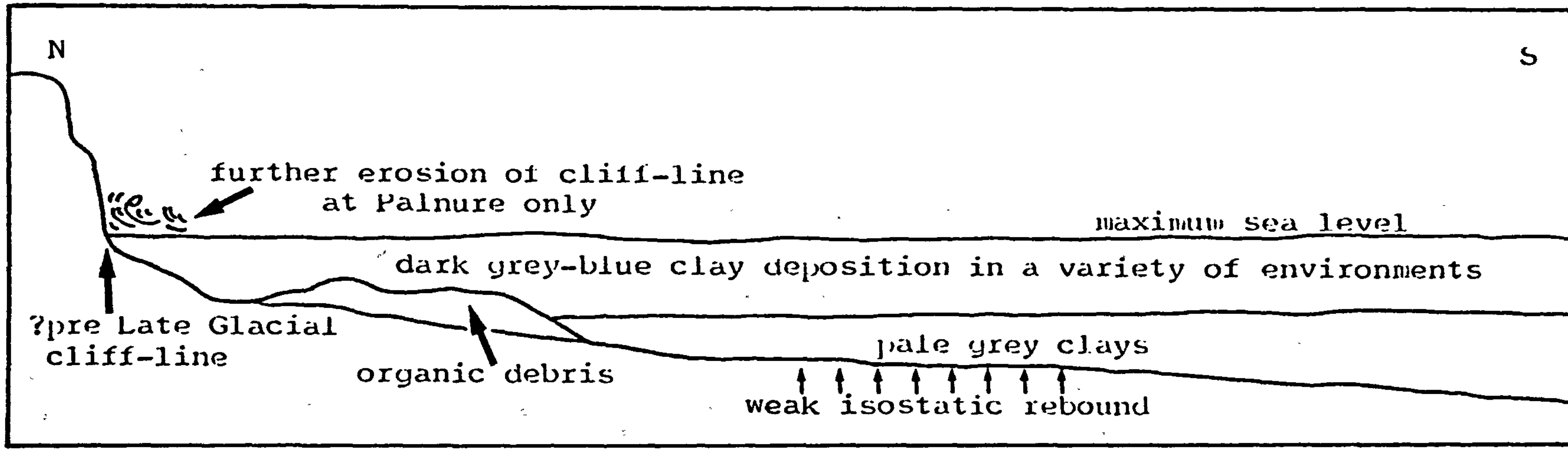


Fig.6.3b North to south section from Palnure to the Cree estuary at Meikle Carse at the maximum of the Holocene marine transgression. NB Scale N to S approximately 1.5 km

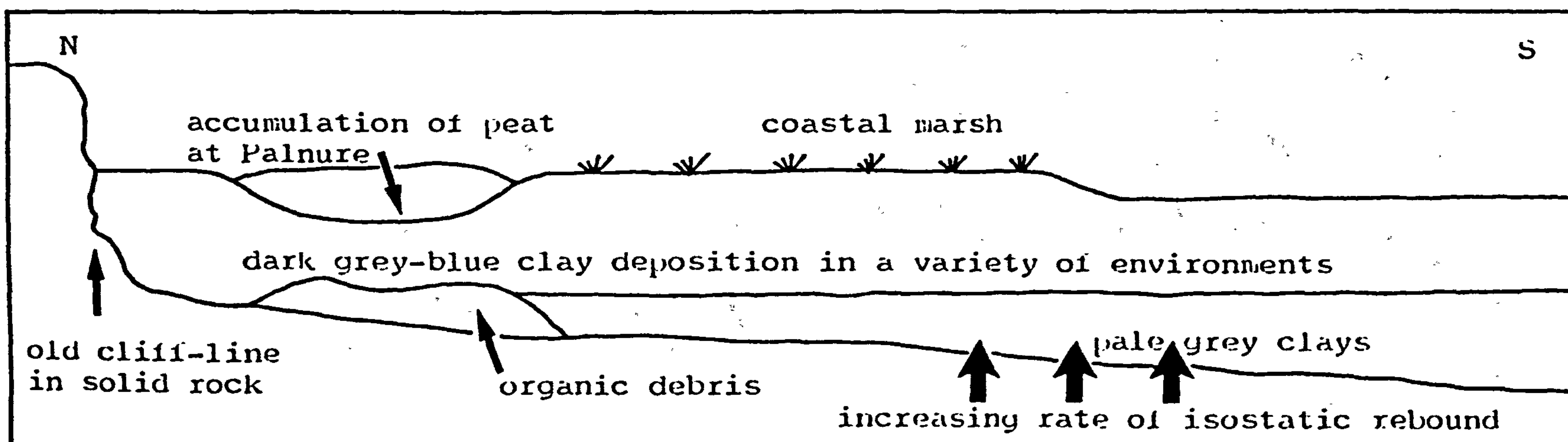


Fig.6.4b North to south section from Palnure to the Cree estuary at Meikle Carse c. 6480 ± 107 years B.P. NB Scale N to S approximately 1.5 km

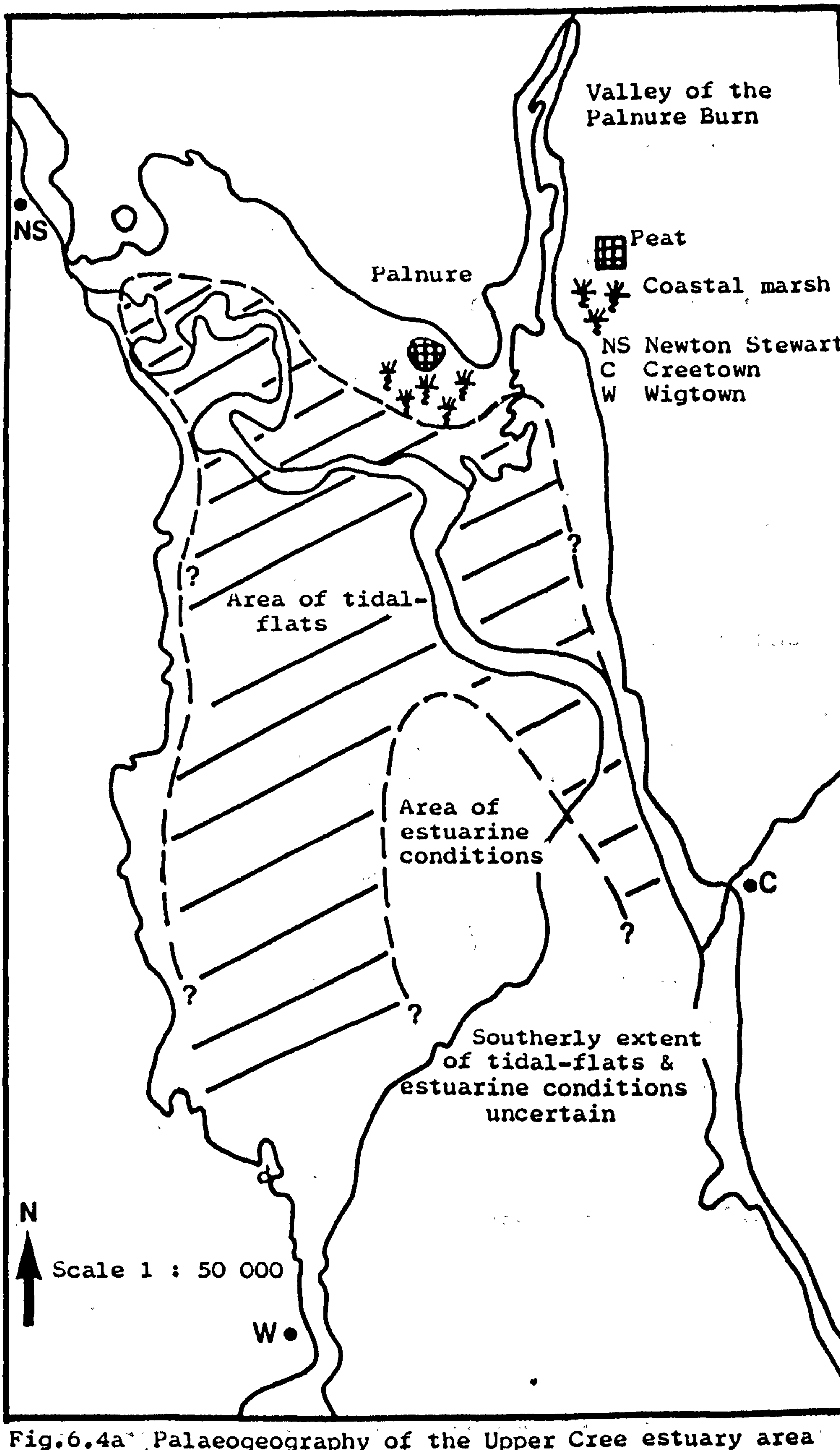


Fig.6.4a Palaeogeography of the Upper Cree estuary area c. 6,480 ± 107 years B.P.

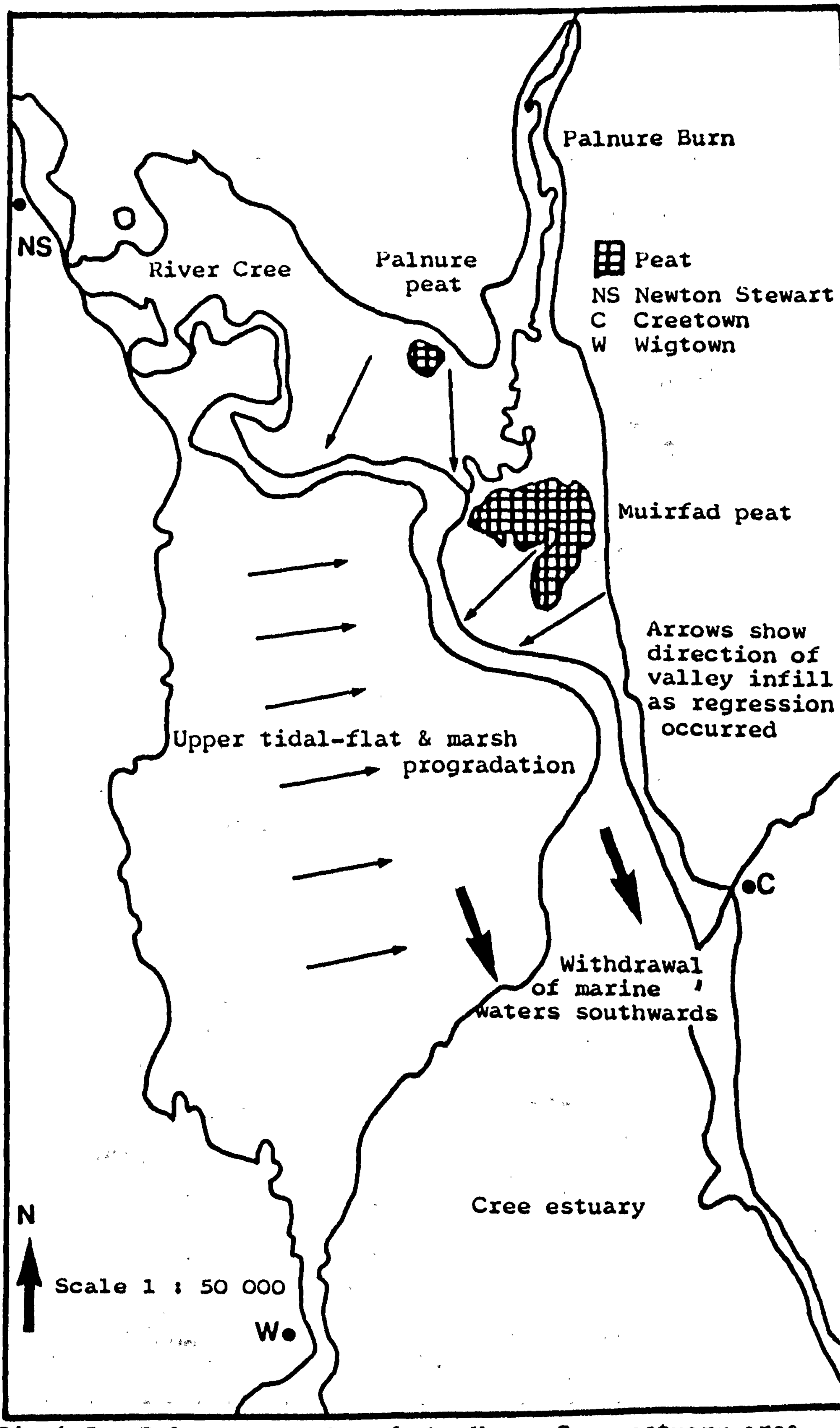


Fig.6.5a Palaeogeography of the Upper Cree estuary area post 5,000 years B.P.

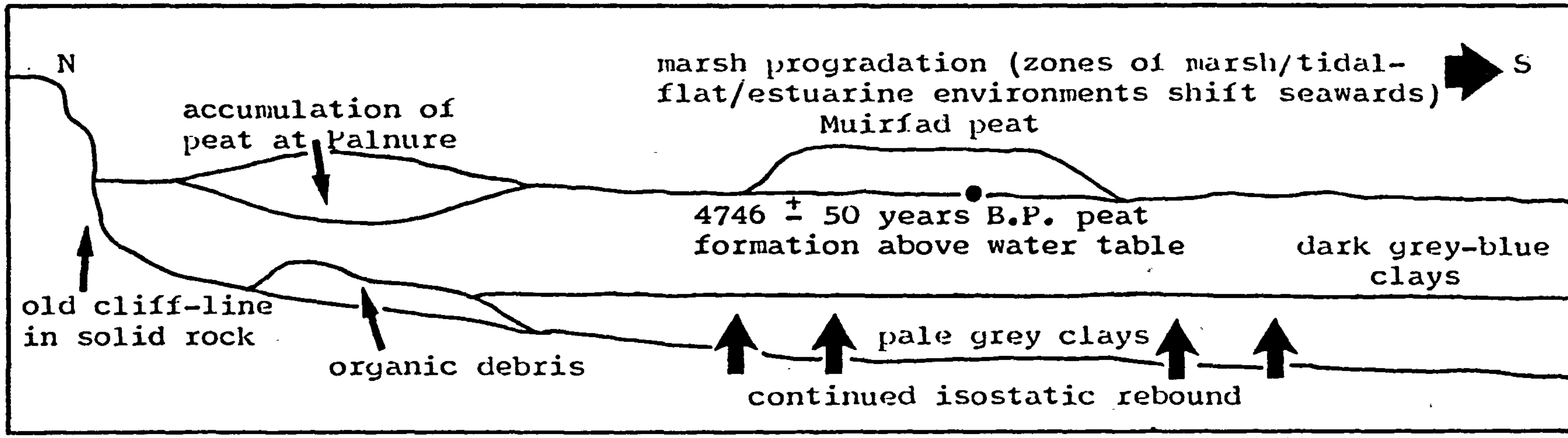


Fig.6.5b North to south section from Palnure to the Cree estuary at Meikle Carse c. 4746 ± 50 years B.P. NB As the water table dropped, successively lower parts of the marsh became drier, changing from brackish to freshwater and colonised by variable vegetation

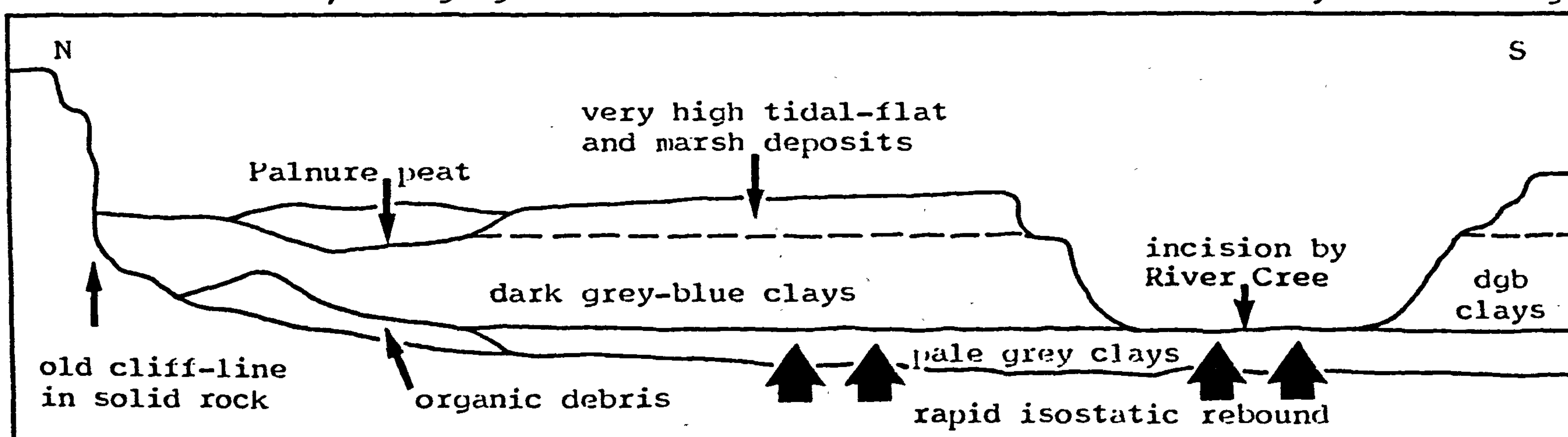


Fig.6.6 North to south section from Palnure to the Cree estuary at Meikle Carse, present day. dgb clays = dark grey-blue clays. NB Scale N to S approximately 1.5km in both sections

incised rapidly from c. 5,000 years B.P. onwards. By 4,746 years B.P. the sea had receded from the area, and terrestrial conditions were established with the commencement of peat formation at Muirfad Flow (Jardine 1975, 185-186). The upper River Cree estuary and Palnure Burn continued to incise rapidly to the present-day (Fig. 6.6, p. 162).

Magempsy (sequence 5, Fig. 6.1) was the only location where the transgression was recorded at its altitudinal and lateral landward limit. The environment there differs significantly from those found elsewhere at the limit of the transgression. The clays at Magempsy bear no evidence of marine influence above NTL, but contain very abundant washed-in terrestrial material. The clays bear a striking similarity to the pale grey clays, possibly due to formation under closely similar circumstances. After penetration of the valley of the Palnure Burn by the sea (after 7,900 years B.P.) the environment was one of a shallow inlet bounded mainly by rock walls. Deposition of fine-grained deposits occurred under weak tidal conditions. As regression ensued, the valley of the Palnure Burn was infilled with upper tidal-flat deposits and finally by marsh, which remained during the formation of a terrestrial environment.

CHAPTER 7 - THE LOWER CREE ESTUARY SECTIONS

7.1 THE A75 CREETOWN BY-PASS SECTION

7.1.1 Introduction

Details of the geology and sequential stratigraphy, along the route of the A75 By-pass at Creetown, and kindly supplied by Jamieson McKay & Partners, are revealed in a preliminary survey, consisting of 27 boreholes and 7 trial pits. The By-pass, presently under construction, extends from Pulwhat Bridge (NX 4650 6110), to south of Creetown at NX 4718 5800 (Fig. 7.1), lying parallel to the adjacent marsh for most of its length. The underlying geology is recorded in a north to south correlated section (Fig. 7.2), described below.

7.2 FACIES DESCRIPTION AND STRATIGRAPHY

7.2.1 The solid geology

Bedrock, encountered in trial pit (TP)8, and in three widely-spaced boreholes, R4, B1 and B3, from north to south respectively, is overlain by stiff glacial till in all three boreholes and one pit. The bedrock/till contact is thought to dip consistently in a southerly and seaward direction, from 6.68m A.O.D. in TP8 to 4.04m B.O.D. in R4, 24.86m B.O.D. in B1 (where bedrock is represented by weathered sandstone and siltstone), and 27.80m B.O.D. in B3, below Moneypool Burn.

The rocks consist of grey mudstones, siltstones and sandstones, exhibiting a variable degree of weathering, which imparts a red colouration to the rock and the immediately overlying till. The red-brown silt and sand at the base of B1 is believed to represent weathered sandstone/siltstone directly above unweathered rock. Bedrock weathering effects indicate that the area was subaerially exposed (i.e. above sea-level), which testifies to the fact that isostatic and eustatic changes have occurred within this region.

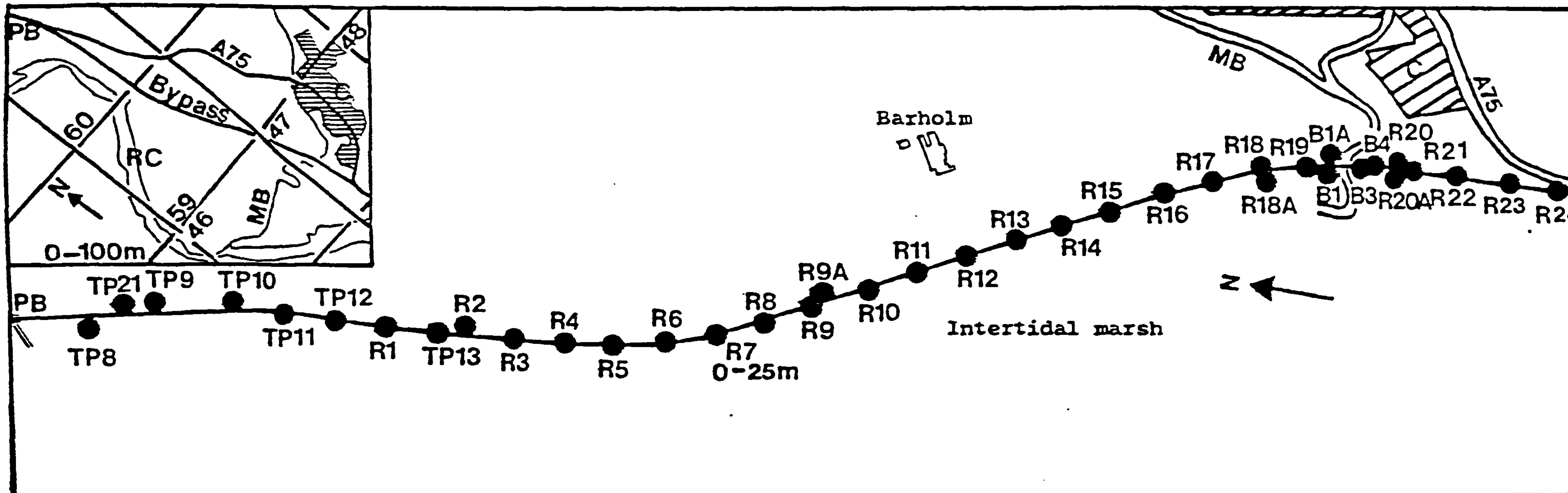


Fig.7.1 Location of boreholes and trial pits, A75 Creetown By-pass. R or B – borehole, TP – trial pit, PB – Pulwhat Bridge, RC – River Cree, MB – Moneypool Burn, C – Creetown

Coloured key applicable to fold out geological sections throughout the thesis

Beach sand (Fig.7.9, p. 197)

Marsh cover (Fig.7.2, p. 167)

Mottled silts & clays with rootlets (Fig.9.1, p. 215)

Very high tidal-flat/marsh infill, peaty in places

Upper tidal-flats (carse clays), Brown-grey clays, Fig.9.1, p. 215

River channel sands & gravels

Lower tidal-flats (carse clays)

Stiff organic clays (Fig.9.1, p. 215)

Fluvio-glacial sands & gravels

Glacial till

Solid rock

Granite (Fig.7.9, p.197)

Metamorphosed sandstones & siltstones (Fig.7.9, p.197)

Fig. 7.2 Geological section, Pulwhat Bridge to the south of Creetown

Scale Horizontal 1:2500 Vertical 1:250 (vertical exaggeration 10 X)

tions TP13 to R6

s and gravels flooring a shallow hollow in the glacial till een TP13 and borehole R6, are best developed in R4, where

7.2.2 The unconsolidated glacial deposits

There are two main types of glacial deposits: glacial till (or clays), and fluvio-glacial sands and gravels.

7.2.2.1 Glacial till

This unit overlies the solid rock throughout the length of the recorded section, reaching a maximum thickness (if the assumed rock/till contact position is correct) on the western flank of Moneypool Burn, between R12 and R15. It appears to be thickest in R14 where an estimated 21.25m of till occurs. The till constitutes a very poorly-sorted silty, sandy clay with highly variable amounts of fine to coarse gravel, cobbles and boulders. The latter were recorded in boreholes TP21, TP9, R3 to R5 and R8. The till has a predominantly grey-green colour but is occasionally dark grey or grey-brown. Close to bedrock, the clay is red or red-brown in colour and often mottled, the colour and mottling being results of weathering effects in the underlying bedrock. The till has a firm to very stiff consistency, but is frequently soft in patches.

7.2.2.2 Fluvio-glacial sands and gravels

The fluvio-glacial sands and gravels, exhibiting a discontinuous, sporadic development throughout the section, rest unconformably on glacial till. The fluvio-glacial sands and gravels are distributed as follows:

<u>Locations TP8 to TP10</u>

Between these trial pits, the fluvio-glacial material, resting on glacial till, forms a veneer of sediment varying between 0.30m and 0.80m in thickness, apparently thinning southwards, eventually to zero, between TP10 and TP11.

<u>Locations TP13 to R6</u>

Sands and gravels flooring a shallow hollow in the glacial till between TP13 and borehole R6, are best developed in R4, where they attain a thickness of 3.40m. The hollow is unconformably overlain by high tidal-flat deposits in TP13 and R2, and by a thin marsh cover between R3 and R6.

Locations R9 to R11

A flat-floored hollow in the glacial till, present between boreholes R9 and R11, is partially infilled by c. 1.50m of sands and gravels, overlain by a thicker development of tidal-flat deposits.

Locations R13 to R15

Here, the fluvio-glacial sands and gravels, "capping" a glacial till mound, are thickest (c. 1m) on its flanks, and 0.80m thick at the crest. The "mound" feature is overlapped on both sides by progressively younger deposits - by lower tidal-flats (between R15 and R16), which are overlapped by upper tidal-flat deposits between R14 and R15 on the southern flank, and by upper tidal-flat deposits to the north at R12 to R13. Upper tidal-flat deposits may have extended over the crest of the mound at one stage, but are now eroded allowing the marsh to rest unconformably on much older fluvio-glacial material.

Locations R16 to R21

South of R15, there is a rapid increase in thickness of the fluvio-glacial sands and gravels, providing a thick infill to the "palaeo-valley" of the Moneypool Burn. Fluvial erosive action has lowered the valley floor (composed of till) to 23.70m B.O.D. in B3, i.e. to within c. 4m of bedrock, the sands and gravels reaching a maximum thickness of 17m at this point.

Nature of the deposits

The fluvio-glacial sands and gravels are of widely variable size-grade, sorting and colour, but consist mainly of fine to coarse sand (which is frequently silty), fine to coarse sub-angular to sub-rounded gravel, and cobbles of local rock types. Frequently in R4, cobbles of mudstone and granite are present. The colour of the material varies through shades of light to dark brown, light to dark grey, green-grey and grey-brown. Upward coarsening and crude stratification of the deposits is well developed in boreholes R19, B1, B3, and R21, as a result of fluvial aggradation under conditions of lowered sea-level.

7.2.3 Post-glacial deposits

7.2.3.1 Lower tidal-flats

In the section, the earliest evidence for a marine incursion occurs in the valley of the Moneypool Burn between R16 and R24. Overlying the fluvio-glacial sediments in boreholes B1, B4, R20 and R21 (preserved in the centre of the "valley" of the Moneypool Burn, and also at its deepest/lowest point, but not represented in Fig. 7.2) are c. 0.75 to 0.80m of fine to coarse sands and fine to medium sub-angular to sub-rounded gravels, considered to represent a transgressive lag deposit, reworked from the underlying fluvio-glacial material. The sands and gravels in turn are overlain by dark (? blue) grey, laminated clays, averaging 5m in thickness, with a known maximum thickness of 6.30m in R21. The clays are frequently silty and soft, containing traces of (? storm) gravel and occasional to frequent layers of shell fragments.

Laminae within the clays were recorded in detail from R18A and R20A, immediately adjacent to R18 and R20 respectively. Laminae varied from 1mm to 3mm in thickness, 2mm to 10mm spacings being present between laminae. In R18A, laminae of the lower tidal-flat sequence between 1.40m and 5.00m B.O.D., showed a 5° to 30° dip, increasing with depth. Since displaced laminae were also recorded at 3.60m to 3.70m B.O.D., it is probable that the dip of the laminae has resulted from slumping within the sediment pile.

7.2.3.2 Channel deposits

Locations R17 to B3

Northward lateral migration of the Moneypool Burn has led to the development between locations R17 to B3 of a sheet-like spread of channel material which appears to be lens-shaped in cross-section. The channel deposits accumulated under stable or slowly falling sea-level conditions, as the meandering Moneypool Burn incised into the lower carse deposits. This phase was followed by unconformable upper tidal-flat progradation over progressively younger lower tidal-flat and channel deposits between R15 and R24. Due to recent fluvial erosion of the tidal-flat between locations B3 and B4, followed by northward channel avulsion by the Moneypool Burn, channel deposits (in B3) are directly overlain by recent marsh sediments. The present channel of the Moneypool Burn is located between B1 and B3.

Channel deposits of the "old" Moneypool Burn occur between 1.24m A.O.D. (in R17) and 2.86m B.O.D. (in B1), giving a possible maximum thickness of over 4m in the recorded section. The channel has a slightly asymmetrical cross-sectional profile, thinning to 1.80m in R17 and to zero before R16. The channel deposits, at their thickest in B1 (3.40m), are composed of fine to coarse sand and sub-angular to sub-rounded gravel with silt. Cobbles, probably derived from the underlying fluvio-glacial material exposed further upstream, are found in R19 and B3.

A thin (c. 0.50m to 1m thick) pocket of channel material, consisting of clayey and silty fine to coarse sand and fine to coarse gravel is encountered in R20 and R21, on a sloping, lower tidal-flat surface that may be a point-bar. It is suggested that this deposit originated in the course of a storm flood that resulted in deposition of a toe of coarse material around the front of a point-bar.

7.2.3.3 Upper tidal-flats

Locations R15 to R24

Between the above-mentioned boreholes, the upper tidal-flat sediments rest unconformably on all older deposits. The tidal-flat sediments are thinnest near the margins of the meandering reach of the Moneypool Burn, e.g. from locations R22 to R24 at the southern end of the section (c. 1m thick), and 2.40m and 3.40m thick in R16 and R15 respectively to the north of the Burn. A slight "hollowing" (erosion) of the lower tidal-flat appears to have occurred in R15, with incorporation into the carse deposits of gravel from the underlying fluvio-glacial sediments. The upper tidal-flat deposits thicken towards Moneypool Burn, averaging 2.50m to 3m in thickness.

The deposits of the flats consist of soft, grey to grey-brown sandy, clayey silt and clay, darkening with depth to dark grey. Fine to coarse sand laminae with shell fragments and pockets of silty fine sand are also present. Laminae, 1mm to 10mm in thickness, spaced 5mm to 20mm apart, and probably exhibiting tidal bedding, were recorded in R18A, B1 and R20A. Additionally, occasional thin layers of clayey, silty, sandy fine gravel and coarse sand, possibly products of storm conditions, were present.

Locations R9 to R12

Between the above-mentioned boreholes, the upper tidal-flat deposits comprise a thick hollow infill, overlapping onto older glacial sediments on the northern flank of the "mound" at R12 to R13, and overlain by progradational marsh deposits from R8 southwards to R11. Early marsh progradation in this area may represent the onset of marine regression (see discussion Chapter 7.3.2). The upper tidal-flat deposits vary from 2.70m to 5.10m in thickness, and they consist of grey, very soft to soft slightly clayey sandy silt, becoming a silty fine sand with depth (i.e. fining upwards). Laminae of silty fine sand are extensive in R9B, varying from 1mm to 7mm in thickness, with spacings of 5mm to 20mm. Between 0.75m and 1.40m A.O.D. in the same borehole, a slump unit was recorded, but it was not noted whether the slump was a result of coring, or a preserved feature. If the latter, then slumping is probably the result of collapse of a tidal creek margin - a common occurrence on the banks of the present-day Moneypool Burn (see Chapter 10.3.2.5 and smaller-scale creeks. The presence of sub-rounded gravel in R12 is due to the reworking of the margin of the hollow by marine/estuarine processes, material being derived from fluvio-glacial gravels (recorded in R13) to the south.

Locations TP10 to R2

A relatively thin covering of very high tidal-flat to marsh deposits is present between TP10 (the most northerly and highest occurrence of upper tidal-flat deposits in the section) and R2. To the south of R2, the upper flats have been removed by erosion, because present marsh deposits rest directly on fluvio-glacial sands and gravels. The erosion at R2 coincides with the limit of the merse, relating to a recent phase of fluvial erosion by the Cree estuary.

The highest occurrence of tidal-flat deposits (probably supra-tidal in nature, as there is evidence of peat) is at 13m A.O.D. in TP10; the lowest occurrence is at 4.24m A.O.D. at the base of a small hollow in R1. Approximately 1m of high tidal-flat/marsh deposits occur in TP10, TP11 and TP12, consisting of firm, dark brown sandy, silty clay with sub-angular and sub-rounded gravel, probably reworked from underlying and adjacent fluvio-glacial material.

Generally, the tidal-flat deposits consist of soft to very soft grey-brown to yellow-brown, mottled and faintly-laminated, silty clay, with fine sand laminae and traces of peat. Lenticular pockets of silty fine sand are also evident. It is suggested that these deposits are very high intertidal to supratidal in character because

1. Traces of peat are present.
2. Shell fragments are absent, i.e. the adjacent flats were above the highest storm tides.
3. Mottling, as a result of oxidation and weathering, is evident.

It follows that the upper tidal-flat deposits between TP10 and R2 are also the oldest upper tidal-flats in the section.

7.2.3.4 Marsh

Locations TP8 to R24

A thin, capping marsh is present along the whole length of the section, unconformably covering all older deposits. Between TP8 and R2, the marsh is represented by brown to dark brown, yellow or grey-brown, mottled, sandy silty clayey topsoil, averaging 0.35m in thickness, and also containing fairly abundant peat traces and rootlets.

Locations R3 to R6

A thin layer (0.15 to 0.35m), of brown and yellow mottled clay or brown silty clay, rests unconformably on fluvio-glacial sediments between R3 and R6. Both the clay and the silty clay contain rootlets and traces of peat.

Locations R7 to R11

It is suggested that a different type of marsh exists between locations R7 and R11, possibly associated with its progradation across a hollow infill, where conditions of sedimentation were physically different to the surrounding marsh. The deposits differ from those described in the above two paragraphs, in that they are dark brown to dark grey, soft to very soft, very silty laminated clays, with grey-brown/dark-grey mottles, rootlets and peat, and are thicker (0.70m to 2.20m) than the firmer clays considered above.

Locations R12 to R24

The capping marsh is absent in two boreholes (B4 and R23) between R12 and R24. Due to the processes of erosion, a step is present between R20 and B3. At the surface of R23, erosion has revealed upper tidal-flat deposits. The marsh deposits vary in thickness between 0.30m and 1.10m, being slightly thicker towards the channel axis of the Moneypool Burn. They also appear to have a sandier nature in the boreholes immediately adjacent to the channel, e.g. R18. The deposits consist of grey-brown, soft to very soft, sandy, silty clay, with frequent rootlets and occasional peat. Thin (1-2mm) laminae, at

10mm to 15mm intervals, are present. Rare traces of shell fragments and fine to medium rounded gravel in R24 are attributed to a storm surge event, sediment being deposited during exceptionally high tides.

7.3 STRATIGRAPHIC HISTORY AND INTERPRETATION OF THE CREETOWN BY-PASS SECTION IN RELATION TO EUSTATIC/ ISOSTATIC CHANGES

7.3.1 Introduction

The post-glacial carse deposits of the Creetown area were deposited unconformably on older glacial sediments, in three hollows, aligned from north to south; only the southernmost (and deepest), from R16 to R21 and presumably to R24, exhibits a full glacial to post-glacial sequence. Elsewhere (i.e. from TP8 to R2, R2 to R6, R6 to R13) erosion has been significant, resulting in widespread unconformity between units.

7.3.2 Stratigraphic history

A gentle N to S sloping bedrock surface is assumed to have been present prior to the development of the Devensian ice sheet. Evidence of weathering and fragments of bedrock in B1 and B3, imply that the rocks were subaerially exposed and that relative sea-level was lower than at present, by c.28m (the deepest occurrence of weathering in the section).

With the onset of glaciation, the Cree valley area was gradually covered by an ice sheet that advanced seawards and deposited large quantities of glacial till from its base in an irregular, hummocky fashion. This irregularity was later modified by fluvial and subaerial erosion. The glacial till is of no great thickness from B1 to B4, having been considerably eroded by subsequent fluvio-glacial action. Sea-level was probably low throughout the time of deposition of the till.

The fluvio-glacial sediments that overlie the till were deposited during a period of ice ablation towards the close of the Devensian Age, when sea-level was low but rising. These deposits are best preserved in R14 to R21 (and probably extend southwards below R24), where they infill the "palaeovalley" of the Moneypool Burn, levelling out irregular features. They consist of alternating gravel and sand layers, including cobbles laid down under very high energy fluvial conditions. Further upstream, at NX 4793 5963, east of Creetown, the Moneypool Burn has eroded a channel through thick fluvio-glacial deposits, flanked by steep cliffs.

Along the remainder of the section, from locations TP8 to R15, the fluvio-glacial deposits have a patchy distribution, forming the floor of hollows R2 to R6, and R9 to R11 and capping the glacial mound below R13 and R15 (Chapter 7.2.2.2 above). Presumably the deposits were much thicker originally, but erosion followed by deposition of the overlying upper tidal-flats, has obliterated them, resulting in their patchy distribution outside the "basin" of the Moneypool Burn.

During early-to mid-Holocene times sea-level was rising, so that the marine waters of the northerly-penetrating Solway Firth eventually flooded the valley of the Moneypool Burn and deposited a transgressive lag of sand and gravel, reworked from underlying fluvio-glacial sediments. The environment was transformed into one of low tidal-flats, with deposition of horizontally-laminated muddy clays with frequent shell bands. The clays overlap onto older fluvio-glacial sands and gravels at R15. The time gap at the fluvio-glacial/lower carse (tidal-flat) boundary may be considerable because the transgression may have persisted later in the western Solway Firth than in the east (Jardine 1980, details of transgression in eastern Solway Firth). The transgressive event itself was very short-lived. It appears that not sooner had the sea reached its maximum lateral and altitudinal extent, than sea-level was once more falling and the marine waters receding.

Overlying the lower tidal-flats is a lens-shaped spread of channel deposits of the Moneypool Burn, representing lateral migration of the burn across its floodplain. The channel deposits are overlain by a sequence of upper tidal-flats which overstep progressively older deposits between R15 and R17, and rest on fluvio-glacial sediments between R14 and R15. Between B1 and B4, the upper tidal-flat deposits are absent, having been eroded by present-day lateral migration of the Moneypool Burn. Consequently, modern marsh deposits rest directly on channel-floor material. The channel of the Moneypool Burn is migrating northwards at this point.

Elsewhere, upper tidal-flat sediments rest directly on fluvio-glacial sands and gravels, without intervening lower tidal-flat deposits, presumably because the area was too high for lower tidal-flat conditions to exist. Between R2 and R6, the upper tidal-flats are eroded away completely, or possibly never formed in this area as R2 and R6 are situated where the inter-hollow divide occurs. Correspondingly, the thinnest upper tidal-flat development is between TP10 and R2, at the furthest point from transgressive influence.

The whole section is overlain by a veneer of marsh deposits, which rest unconformably on all older units. Between R6 and R12, the marsh deposits overlying a deep hollow appear to have a different composition from the marsh deposits elsewhere, possibly due to slight differences in water chemistry, levels and sedimentation patterns within this microenvironment. If sedimentation occurred under brackish water conditions, this suggests that the marsh at these locations began to prograde at an early stage in the regression of the sea from the area, whilst the area immediately adjacent to the Moneypool Burn (R12 to R24) retained its estuarine/tidal-flat characteristics longer, until progradation of the present-day salt-marsh. The latter is frequently downcut by a system of deep creeks of varying size, which form a dendritic pattern in plan view.

Probably sea-level either was at its (Holocene) maximum altitude during deposition of the upper tidal-flats, or had already begun to fall. Certainly it was falling during conditions of marsh progradation and it has continued to fall to the present-day, as testified by the active erosional downcutting of the Moneypool Burn.

7.4 THE CASSENCARIE BOREHOLES

Introduction

The four Cassencarie boreholes, aligned in an approximate NW to SE direction are situated to the south of Creetown (Fig. 7.3). Two major facies were recorded, that of a dark grey or grey, sandy clay, and interbedded, laminated fine to coarse sands and fine to coarse gravels. Both facies contained variable amounts of shell debris, often concentrated into discrete layers, or forming shell "banks" in the coarser lithology. The environments represented in the boreholes are those of a high inter-tidal flat (represented in Cassencarie borehole 4), overlain by the development of an estuarine beach, formed by the accretion of landward-migrating shore-parallel bars during storm surges.

No attempt has been made to match the sequences in the four boreholes since Cassencarie boreholes 1 to 3 are too shallow. The most comprehensive borehole is Cassencarie 4, upon which environmental interpretation is based, together with supplementary evidence from the other three boreholes. Due to the nature of the environments represented in the boreholes, contacts between units are assumed to be sharp and are shown as such in the graphic logs (see Appendix p.349 - 350). The four boreholes are now described.

7.4.1 Cassencarie borehole 1

Cassencarie borehole 1 (Appendix p.349), located at NX 4741 5723 and extending from 3.68m to 5.95m A.O.D. consists of 2.27m of interbedded gravels, gravelly sands and shell layers. Between the base of the borehole at 3.68m A.O.D. and 4.58m A.O.D., 0.90m of alternating gravelly sands and sandy gravels, containing shell fragments, are recorded. Shell debris, together with dark organic sand and fine gravel, forms beach laminations between 4.43m and 4.58m A.O.D. Two samples,

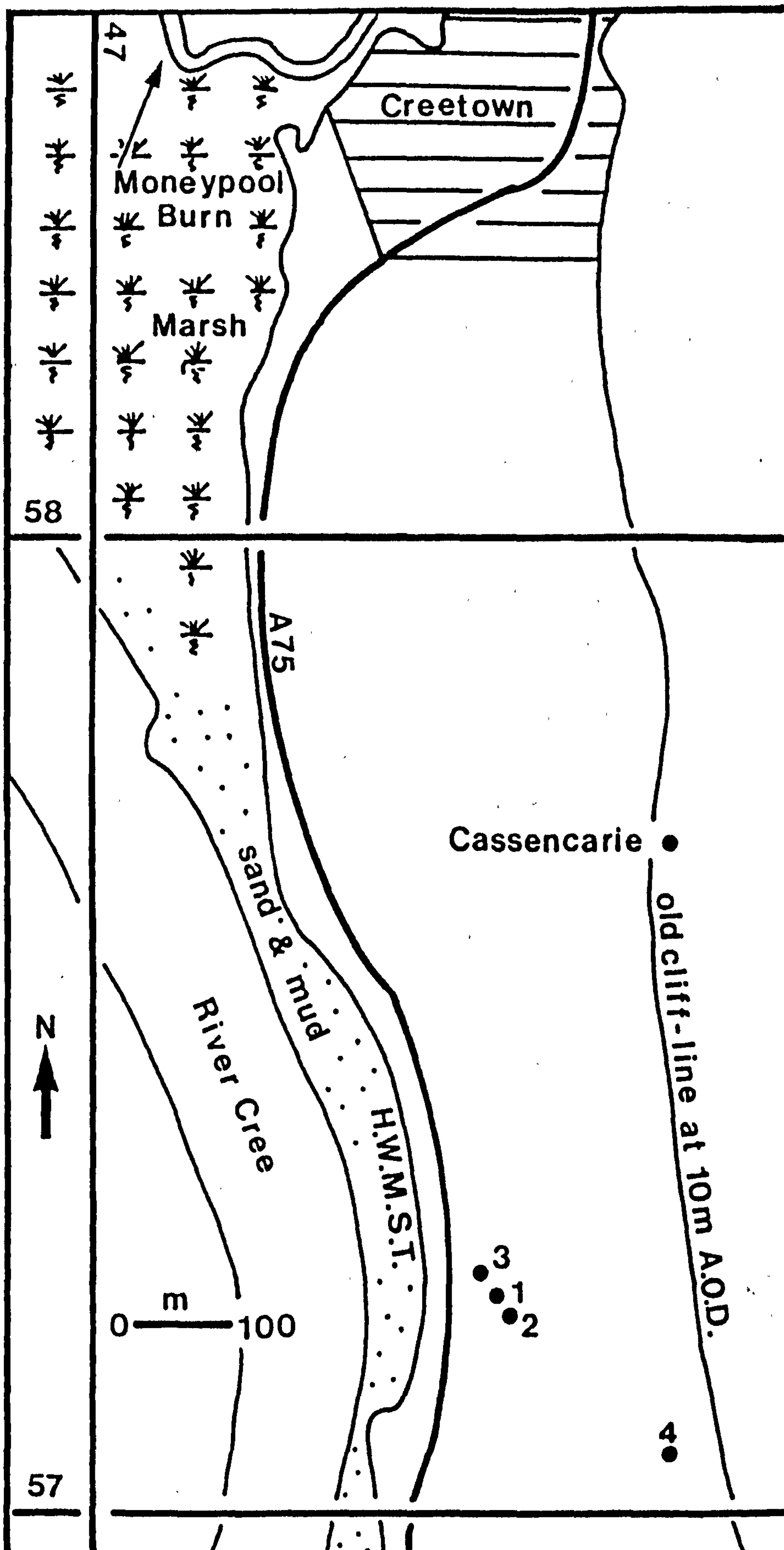


Fig.7.3 Map to show location of Cassencarie boreholes (numbered)

at 4.12 to 4.19m and 4.58m A.O.D. (Cas1 S2 and Cas1 S1 respectively), yielded evidence to support the presence of a high energy environment. Shell debris was highly abraded and evidence of infauna was absent. Rare occurrences of foraminifers (only four examples were recorded in both samples) suggest that these microfossils had been washed in.

The gravelly sands are overlain by firstly 0.08m of very coarse, pebbly gravel (from 4.58m to 4.66m A.O.D.), followed by 0.45m of pure shell material, from 4.66m to 5.11m A.O.D., composed of the remains of the bivalves Cerastoderma edule, Mytilus sp., Tellina sp. and the gastropod Turritella sp. The bivalves, chiefly adult specimens of C.edule, are wholly disarticulated, but valves remain unfragmented and relatively unworn. This suggests the erosion of a nearby community, followed by a short period of transportation to the site of deposition. Greensmith & Tucker (1969), consider that the bulk of such shells are derived from living communities near low water mark and from sublittoral communities, particularly those living in adjacent estuary channels.

The gravels and shells are interpreted as products of a storm surge event - the pebbly gravels being deposited first, followed by the development of an overlying "shell ridge" or bank under waning energy conditions. The gravel/shell unit constitutes a storm ridge.

The lower storm ridge is overlain by a further storm deposit between 5.11m and 5.65m A.O.D. The basal 0.25m of this storm unit consists mainly of pebbly gravel with some cobble material, fining upwards to sandy fine gravel containing frequent fine shell fragments. The topmost 0.30m of the borehole consists of a brown loamy topsoil.

7.4.2 Cassencarie borehole 2

Cassencarie borehole 2 (Appendix p.349) located at NX 4743 5721 and extending from 4.96m to 6m A.O.D., consists of 1.04m of fine sand overlain by shell material and topsoil. A 0.04m fine sand/shell layer (from 4.96m to 5m A.O.D.) rests on gravel at the base of the borehole. The storm-generated gravel proved too coarse to be penetrated successfully. The fine sand/shell layer is in turn overlain by 0.71m of brown laminated fine sand (a beach deposit) which is sampled between 5.24m and 5.32m A.O.D. (Cas 2 S1). The sample yielded frequent finely crushed shell remains and rare washed-in foraminifers - evidence of a high energy environment. The foraminifers were tentatively identified as Elphidium sp. as they were sufficiently abraded as to preclude further identification to specific level. The presence of very abundant flaky muscovite mica within the deposit suggests that it is a typically immature estuarine sand.

The brown sand is overlain by a 0.07m storm shell layer between 5.71m and 5.78m A.O.D., followed by c. 0.22m of shelly loamy topsoil.

7.4.3 Cassencarie borehole 3

Cassencarie borehole 3 (Appendix p.350)located at NX 4740 5725 and extending from 5.02m to 5.79m A.O.D. consists of 0.77m of mainly grey fine sand overlain by a storm shell layer and top-soil.

Between 5.02m and 5.54m A.O.D., 0.52m of grey, faintly-laminated beach sand is recorded. The sand is sampled from 5.02m to 5.11m A.O.D. (Cas3 S2). The sample yielded an abundant organic component but no shell material. This, together with a high abundance of mica, suggests that the sand has an estuarine source. The deposit represents a relatively low-energy beach environment.

In contrast, the grey sand is overlain by a 0.10m thick storm shell layer (sampled between 5.54m and 5.64m A.O.D. (Cas 3 S1), definitely derived from a more marine source. Main components of the sample were disarticulated whole valves of the bivalves Cerastoderma edule and Tellina sp. and the gastropods Turritella sp. and Littorina sp. Echinoderm spines were common in the finer fraction.

The _Cerastoderma edule_ valves, although completely disarticulated, were not totally fragmented. All adult valves were counted and it was observed that an equal number of left and right valves was present. This, together with the fact that a considerable number of young adult and juvenile forms were recorded, suggests that the shells are derived from a living community but not sorted and transported a great distance to their site of deposition. The valves, however, have been subjected to a certain amount of post-mortem mechanical abrasion and partial disintegration during transportation, since many have their umbones (the weakest part of the shell), firstly smoothed and then "punched out". Erosion and/or dissolution of shell material along the margin of the concentric growth lines, particularly in the "old" adult valves where growth lines are well developed, is also apparent (see Hollmann 1968). In addition, the radial ribbing is often worn or reduced around the umbones leaving the shell surface smooth. A small proportion of the shell valves is heavily stained by an iron residue. It is suspected that the valves concerned are derived from already partially consolidated shelly/gravelly deposits. A few examples of bored shell valves were recorded. A _Tellina_ sp. valve exhibited a _c_. 1mm wide hole with a bevelled margin, near its umbo. The bevelling is typical of predation by a boring organism.

It has previously been suggested that the shell layer has been derived from a marine source and under storm conditions. This is confirmed by the presence of echinoderm spines, together with the existence of the flat periwinkle, _Littorina littoralis_ - often found on the middle and upper parts of the lower shore - and fragmented _Turritella_ sp., extremely common in muddy gravel at "moderate depth" and frequently found washed up after stormy weather.

The fairly common presence of typically estuarine hydrobid gastropods (albeit as mostly crushed fragments), however, suggests that the more marine material has been subject to mixing with material of an estuarine character.

Derivation of material from a much older unknown source is implied by the presence of two examples of thick-walled, presumably arctic, species of gastropod genera, which remain unidentified.

Foraminifers (probably washed in) are generally rare to occasional and difficult to identify due to the crushed nature of the specimens. This reflects the inhospitable nature of the environment during the deposition of the sediment.

In conclusion, it can be observed that the shell layer of Cas3 S1 has a generally marine but more varied source than the other samples from the same borehole.

7.4.4 Cassencarie borehole 4

Cassencarie borehole 4 (Appendix p.350)located at NX 4759 5707 and extending from 3.01m B.O.D. to 5.02m A.O.D., consists of 8.03m of dark grey clays overlain by a development of storm beach ridges.

Between 3.01m B.O.D. and 0.01m A.O.D., 3m of dark grey clay with occasional pebble and shell layers were recorded. The clay was sampled at c. 2.92m B.O.D. (Cas4 S11), 2.16m B.O.D. (Cas4 S9) and 0.09m B.O.D. (Cas4 S8).

A strong marine trend for source of material is observed in the samples from 2.92m to 1.40m B.O.D. (i.e. marine influence decreases up the borehole). The main components of Cas4 S11 (at 2.92m B.O.D.) were diverse, with generally common remains of bryozoans, ostracods, foraminifers, echinoderm test fragments and an arthropod claw. The presence of hydrobids (particularly Hydrobia jenkinsi) and Cerastoderma edule fragments, however, confirms that the environment is still estuarine since Hydrobia jenkinsi is a brackish-water species. In addition, there is a high abundance of washed-in plant material which implies that the site of deposition is reasonably close to land. Material from Cas4 S10 at 2.16m B.O.D. is similar to that of Cas4 S11. Again, a high abundance of plant material was noted, together with very abundant mica. This implies the closeness of the site of deposition to a terrestrial location and the immaturity of the sediment since mica is well preserved. Cas4 S9, situated at 1.40m B.O.D., yielded abundant mica, plant fragments and woody debris, together with vivianite fragments and hydrobid shells - all supportive evidence for the presence of an estuarine environment of deposition. However, there is still a considerable input of debris from a marine source, with common echinoderm spines, sponge spicules and bryozoan remains. Cas4 S8, at 0.09m B.O.D., exhibited a loss of marine influence. Possibly it was located on a higher part of the intertidal flat. Abundance of shell remains is low.

In an unpublished study of the microfauna (*i.e.* foraminifers and ostracods) of samples Cas4 S7 to S11, W.E. Boyd recorded the presence of the ostracods *Leptocythere castanea* and *L. lacertosa*, both common mildly-brackish or salt-marsh ostracods, with *L. castanea* being the more low-salinity tolerant of the two (Whately *et. al.* 1971). *L. castanea* includes both adult and juvenile carapaces and valves suggesting that the material is *in situ* and relatively undisturbed by transportation. This further implies that the environment in the immediate vicinity of the site of deposition was of low energy, the brackish nature of the fauna suggesting the existence of a stable (? high) intertidal flat.

A study of the foraminifers from the same samples reveals a high faunal dominance and low faunal diversity, indicative of severe conditions in the nearby environment.

Elphidium excavatum, characteristic of inner shelf shallow waters between 0 and 18m depth, dominates all samples. It has a wide salinity tolerance, ranging from fresh water to salinites of about 30‰ (Boltovsky & Wright, 1976). E. articulatum, also recorded, has a narrower range, being found on sandy tidal-flats in the Firth of Clyde area at present (Abou-Ouf, 1974). E. excavatum is typical in a thanatotype recognised by Abou-Ouf (1974) in the Clyde where there is evidence of strong current agitation. Murray (1973) suggests that since E. excavatum lives 0.05 to 0.06m below the sediment surface it is often unaffected by transport processes and so can live in areas of strong current. Ammonia beccarrii, typical of water depths of 0 to 50m, shows wide environmental tolerance, being found in marsh channels to beach environments (Murray, 1973).

Other species present in the samples are typical of shallow-water marine coastal conditions. E. crispum is found in coastal rockpools and Textularia and Quinqueloculina are typical of a shallow water (5 to 45m) thanatotype described by Abou-Ouf (1974) in the Firth of Clyde.

The faunal remains suggest that in situ fauna indicates shallow marine coastal conditions, with a certain amount of agitation from currents. The low diversity, high dominance and wide environmental tolerance of the dominant species E. excavatum suggests severe conditions. The fauna is probably from an intertidal mudflat area.

Abou-Ouf (1974) does not describe any comparable modern thanatotype in the Firth of Clyde area. The nearest is his thanatotype III, typical of the intertidal sand flats of South Annan sands in the eastern part of the Solway Firth. In this thanatotype E. excavatum is absent, only appearing as a major component in thanatotype I, which occurs at the deep end of the depth range for E. excavatum but is typical of muddier sediments.

The Cassencarie samples Cas4 S7 to S11 indicate that a severe environment persisted throughout the period represented by the basal dark grey and grey clay units from 3.01m B.O.D. to 0.76m A.O.D. The latter unit consists of 0.75m of grey clay with shells and medium to coarse (pebbly) gravel from 0.01m to 0.76m A.O.D. The grey clay is possibly dark grey clay reworked under increased energy conditions - a pause in regression ?. This was followed by a sudden change in conditions and a period during which either no fauna survived here or all the remains were washed out. The grey clay is overlain by a 0.79m thick unit (from 0.76m to 1.55m A.O.D.) of sandy, coarse gravel fining upwards to medium to slightly coarse gravel and coarse sand. The unit contains frequent washed-in shell material such as Ostrea and Littorina sp. fragments, together with wood debris. Samples taken at 1.28m A.O.D. (Cas4 S5) and 0.98m A.O.D. (Cas4 S6) yielded no foraminifers or ostracods - presumably the environment was unstable and not conducive to their existence. Material is extensively transported. Faunal remains, therefore, are likely to be crushed or washed out. The coarseness of the storm ridge material is also significant, since foraminifers and ostracods are hardly likely to survive intact in gravel grade sediment. Examples of Littorina littorea, common on middle rocky shores, and Venerupis decussata (disarticulated but both valves present), common in muddy gravel and sand on the low shore, were present. Lithic material greater than 1000μm (i.e. 1cm) in Cas4 S5 was sub- to well-rounded, attesting to the high energy of the environment. The unit represents a storm gravel ridge on the muddy intertidal flat.

A return to more stable, but brief (lower energy), intertidal mudflat conditions is recorded in the overlying sandy clay, present between 1.55m and 2.34m A.O.D. and sampled at 1.74m to 1.89m A.O.D. (Cas4 S4). It is suggested that the unit of sandy clay from which the sample was taken has been reworked during a pause in regression, hence accounting for the marine input of material. The sandy clay contains abundant shell fragments, including Ostrea sp., and Sepia sp. remains, together with fairly common to frequent echinoid spines and frequent to abundant bryozoan fragments (stick and fenestrate types). Foraminifers are frequent in the finest fraction whilst ostracods are occasional. Indeed the fauna implies that less severe conditons existed than previously. The (? more marine) sand content in the sediment is reflected by the increased proportion of E. articulatum. E. articulatum favours hyposaline conditions, suggesting that earlier restrictions upon the fauna may have been due, at least partly, to salinity.

The development of the estuarine storm beach is best recorded above 2.34m A.O.D. where ridges coalesce. Between 2.34m and 3.98m A.O.D. there is an apparently structureless fine gravelly coarse sand with shell fragments sampled at 3.04m A.O.D. The sample yielded Ostrea sp. fragments and gastropod remains. The lack of foraminifers and ostracods is attributed to the high energy of the environment. The gravelly coarse sand is followed by 0.05m of coarse sand, and a fining-upward storm ridge unit between 4.03 and 4.63m A.O.D., composed of (from the base upwards) medium to fine sandy gravel and fine shell sand which is partly laminated. Some whole shell layers are present in the latter unit (evidence of beach sorting), and there are occasional cobbles. The storm unit is overlain by 0.10m of fine grey sand with shells, a 0.12m shelly loam layer and 0.18m of topsoil.

7.5 ENVIRONMENTAL INTERPRETATION OF THE CASSENCARIE BOREHOLES

Environmental interpretation is based upon the most comprehensive borehole available, Cassencarie borehole 4, together with supplementary evidence from Cassencarie boreholes 1 to 3 (Fig. 7.4).

Cassencarie borehole 4 exhibits sedimentological evidence of the changing conditions of environmental energy brought about by the pause in the Holocene marine regression c. 2,000 years B.P. Prior to this time (? horizontally) bedded muds were

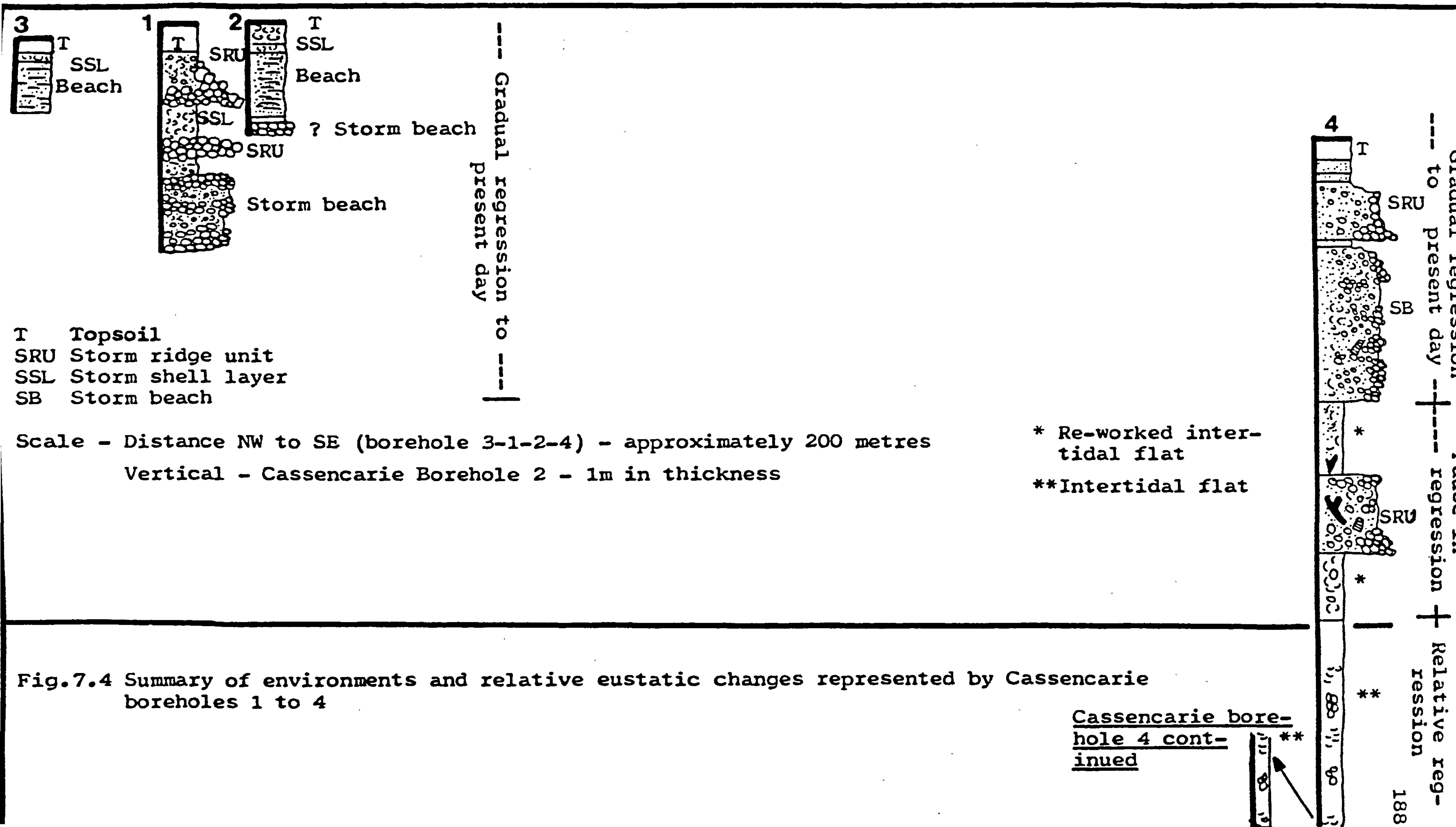


Fig.7.4 Summary of environments and relative eustatic changes represented by Cassencarie boreholes 1 to 4

accumulating in an actively prograding intertidal mud-flat environment, under regressive marine conditions. The energy of the environment was relatively low. An abrupt change in environmental energy initiated by the meteorologically-induced pause in regressive conditions (i.e. the energy increased) resulted in a reworking of the intertidal flats (e.g. grey clay and sandy clay of Cassencarie borehole 4) and the development of storm ridge units. The latter were derived from coarse sediment driven, under storm surge conditions, from the adjacent shallow estuary onto the intertidal flats (between L.W.M. and H.W.M.). The sediment took the form of migrating shore-parallel bars. Around and immediately above H.W.M. the storm ridge units are termed "beach ridges", defined as "continuous linear mounds of rather coarse sediment near the high water line" (Reineck & Singh 1980, p. 352). Unfortunately, in the case of the Cassencarie boreholes, the position of H.W.M. cannot be precisely established. The ridges, therefore, are known as storm ridge units, which are present within a beach environment. Gradual fall in sea-level to its present-day position occurred under stormy conditions, resulting in the progradation of the beach environment and the crude (large scale) alternation of "normal" (? fairweather) laminated coarse-grade, fining-upward storm ridge units, products of waning energy of storm surges. The beach phase of deposition was eventually abandoned in favour of a return to prograding estuarine tidal-flat conditions, presently occurring adjacent to the Cassencarie area.

Combined study of aerial photographs and ground mapping has revealed additional evidence for the existence of storm-generated features. It is possible to establish the positions and postulate on the development of the following:

(a) Former NW - SE trending shore-parallel ridges (Fig. 7.5), developing on the former intertidal flat (i.e. level surface of the carse clays). The ridges, which constitute the storm units of the Cassencarie boreholes, coalesce to form a beach cover.

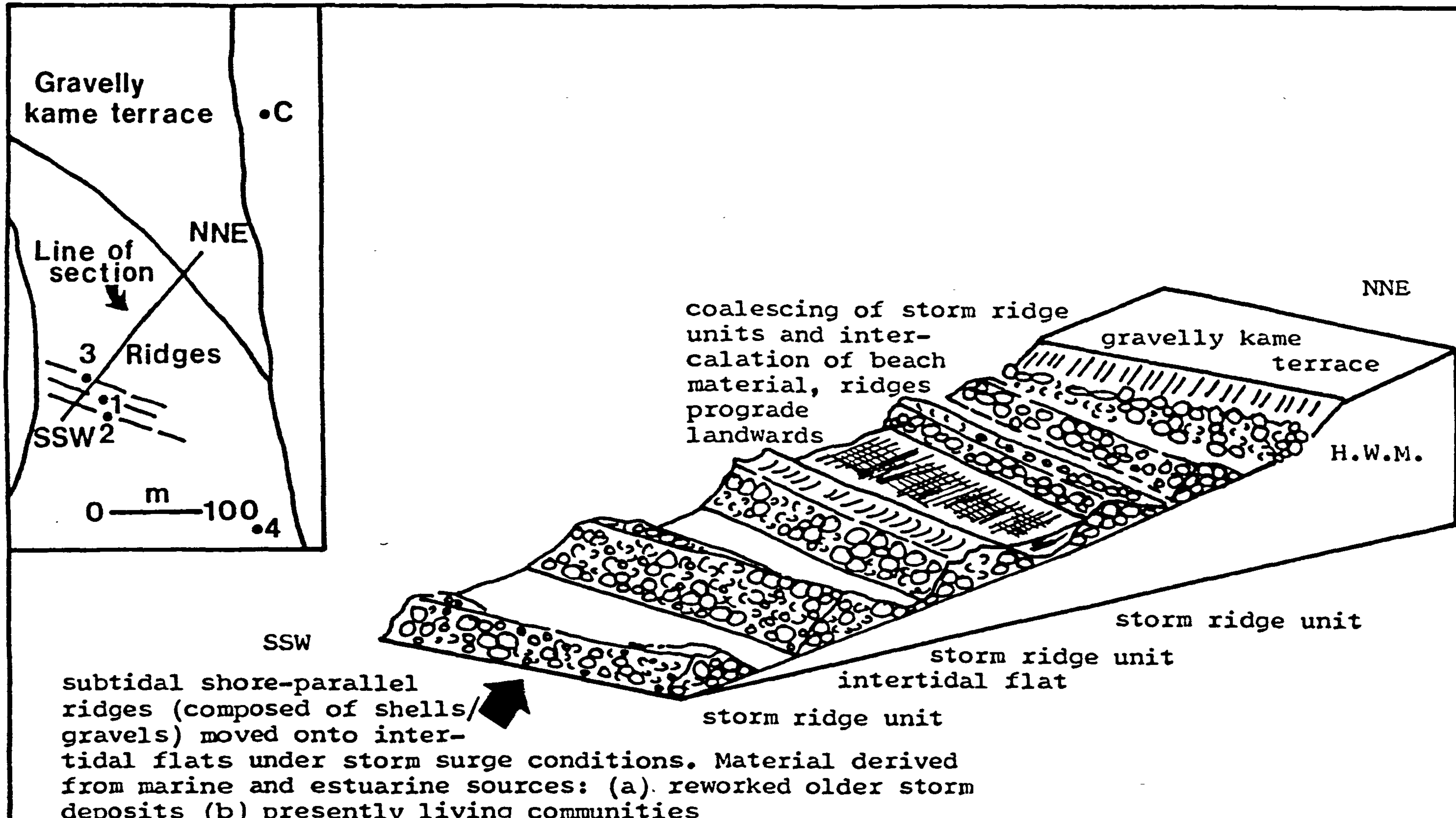


Fig.7.5 Map to show position of shore-parallel/oblique ridges south of Creetown, together with a NNE to SSW section exhibiting the salient features of the ridges. Map - C - Cassencarie. Cassencarie boreholes numbered 1 to 4

(b) A spit to the south of Creetown (Fig. 7.6), constructed by the accretion of gravel ridges from the western (seaward) side. The development of these above features is now considered.

Shell/gravel ridges between Creetown and Carsluith are documented by Jardine (1971,1975), as being products of a constructional phase of deposition during a temporary halt stage in the recession of the Holocene sea from Wigtown Bay. Radiocarbon dating of Cerastoderma edule shell material from Hollanbank (NX 482 555), yielded a date of 2,027 ± 108 years B.P. (GU-374, Ergin et.al. 1972). The constructional phase of deposition c. 2,000 years ago was due partially to changing meteorological conditions, when a particularly stormy phase occurred, strong dominant S and SW low pressure cyclonic conditions being responsible for driving the shore-parallel ridges onto the tidal-flat. Formation of shell/gravel ridges and the spit at Creetown probably took place contemporaneously. The sequence of events prior to and during the temporary halt in regression is now discussed.

At a time prior to c. 2,000 years B.P., normal regressive marine conditions were in progress on the eastern bank of the Cree estuary in the vicinity of Creetown and Cassencarie. A N to S extending gravelly kame terrace (Fig. 7.6), backed on its landward side by the remnant cliff line at 10m A.O.D., was flanked on its western margin by high intertidal mudflats (environment as established in Cassencarie 4). It is envisaged that the gravelly kame terrace margins lay very near to (the "old") H.W.M. or slightly above it, and the undulating surface of the terrace was punctuated by a large kettle hole at Cassencarie (c. NX 4735 5780). The northerly extension of the terrace is uncertain but was probably in the low ground at or around O.D.; this area was later flooded.

The intertidal mudflats were presumably actively prograding in a westerly direction. Their extent is unknown, but coastal

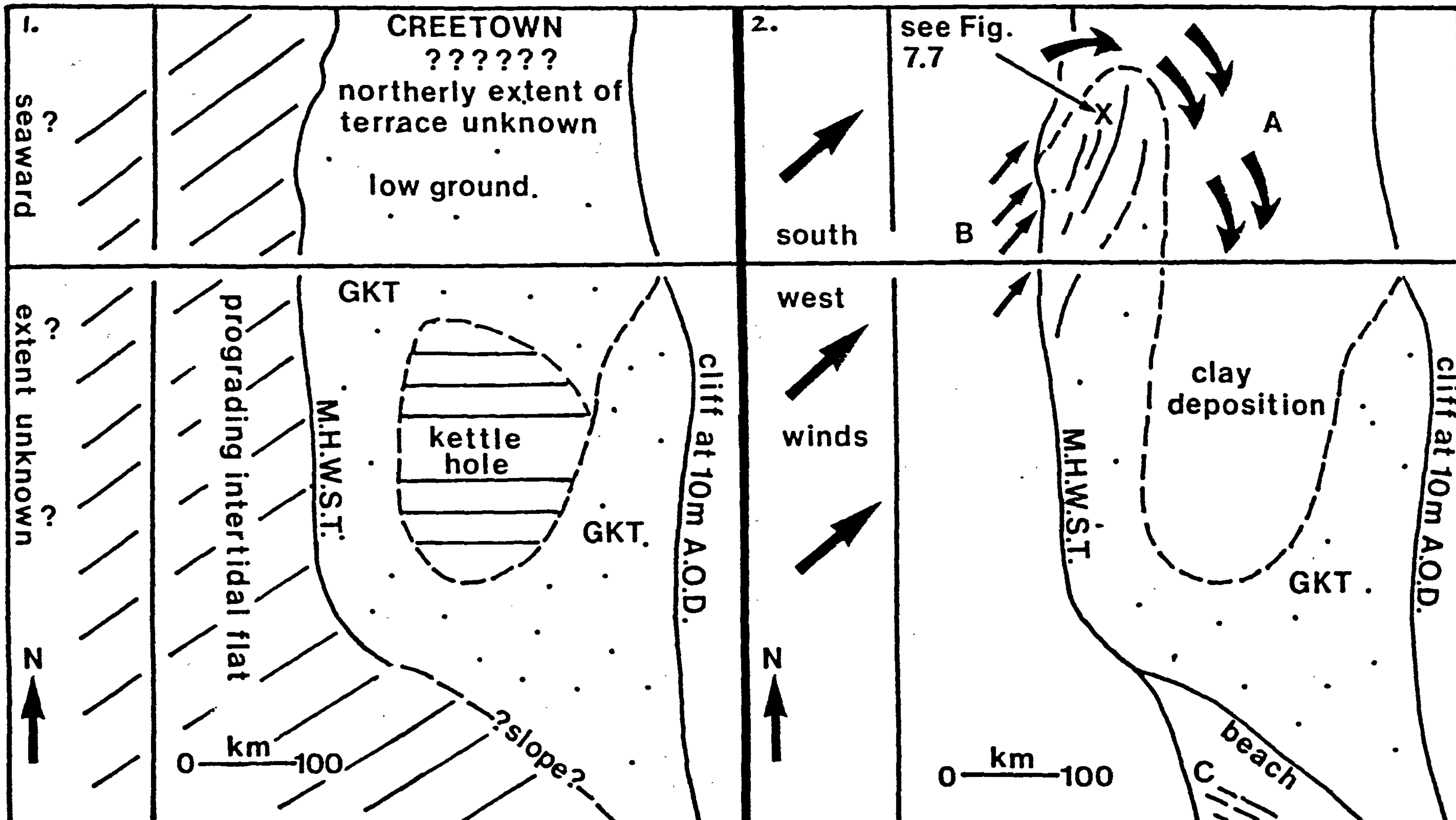


Fig.7.6 Map to show location of gravelly kame terrace south of Creetown and its development during the pause in regression c. 2,000 years B.P. 1. The environment pre-temporary halt in regression. 2. The environment during the constructional phase of deposition, A - Breaching of low ground by marine waters, B - Spit construction, C - Formation of ridges, X - Borehole
GKT = gravelly kame terrace

configuration was probably approximately similar to that of the present-day.

At approximately 2,000 years B.P. a pause in the regression of the Holocene sea from the area occurred. A short-lived transgression occurred. This does not necessarily mean that sea-level rose, only that regression was slowed as a result of deteriorating meteorological conditions that were responsible for constructional deposition and establishment of an environment more marine in character than formerly. The cumulative effect of persistent barometric storm surges, backed by westerly winds, may have resulted in the piling up of water along the coast, with flooding of low lying areas. Wide expanses of land, therefore, would have remained submerged for lengthy periods of time, with depositional conditions "simulating" a transgressive event.

Between Creetown and Cassencarie, the already low lying intertidal mudflats were reworked (as represented by the grey clay and sandy clay of Cassencarie borehole 4), along with the kame terrace margins. The northern margin of the gravelly kame terrace was penetrated by the sea, followed by carse clay type deposition within the kettle hole area. Sediment from the kame terrace was transported seawards to be incorporated into the storm ridge units along with shell/gravel material from an estuarine and/or marine source. Very soon after penetration of the kettle hole, the spit at Creetown formed and the parallel storm ridges were driven onto the intertidal mudflats. The ridges dominate the upper parts of the Cassencarie borehole records.

There is some doubt as to the timing of the formation of the spit south of Creetown. If the formation of the spit predates the incursion of estuarine waters into the carse clay/kettle hole embayment, there should be an absence of carse clays in a hypothetical borehole penetrating the spit at "X" (Fig. 7.6, 7.7). Modification of the kame terrace into a

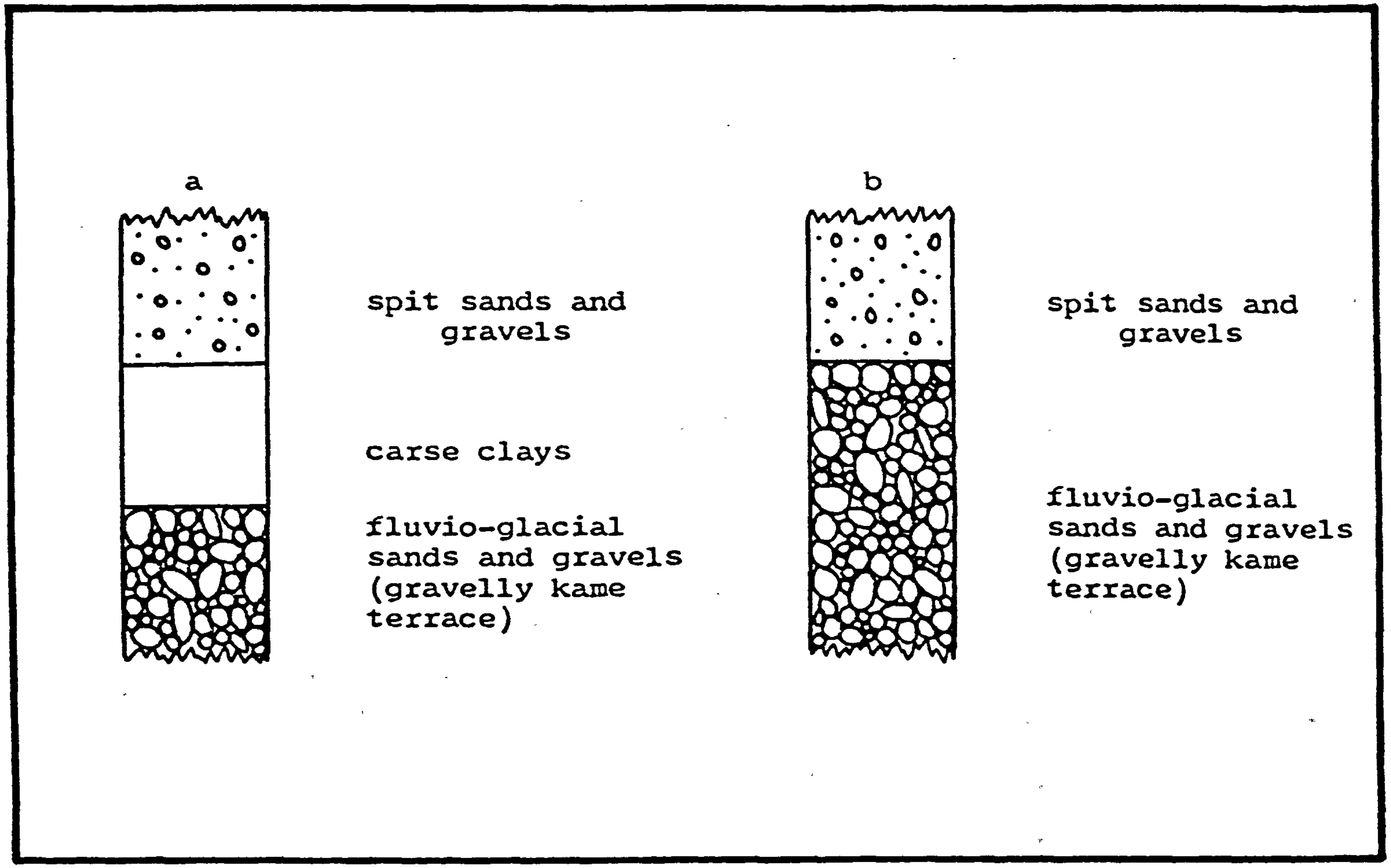


Fig.7.7 Hypothetical sedimentary sequences produced at borehole "X" (see Fig.7.6) if formation of the spit (a) post-dates the marine incursion into the carse clay/kettle hole and (b) pre-dates the marine incursion

spit after marine penetration into the carse clay hollow should produce version 1 of the sequence at X. Modification of the kame terrace prior to carse clay deposition should produce version 2. In both cases the sequence coarsens upwards. To test this theory another borehole must be drilled.

Evidence of the existence of a beach environment in the Carsluith area similar to that at Creetown is discussed in Chapter 7.6 and a summary of the development of constructional features between Creetown and Carsluith is given in Chapter 8.

7.6 THE A75 CARSLUITH BY-PASS SECTION

7.6.1 Introduction and background

Reconstruction of the history of Holocene sedimentation in relation to marine transgression and regression in the vicinity of Carsluith is possible upon the basis of borehole data obtained along the line of the A75 By-pass (Fig. 7.8). The route extends from Glebe Quarry (NX 4781 5636), in the NW, to south of Carsluith at NX 4918 5445. Thorburn & Partners kindly provided the data from their preliminary survey.

A thin, intermittent development of marine carse clays, deposited in the hollows of an undulating fluvio-glacial surface, is observed in a NW-SE geological section (Fig. 7.9). The clays, representing marine transgression on to a land surface, reach a maximum thickness of c. 4m in a hollow NW of Kirkbride Burn, whilst in the vicinity of Kirkbride Burn itself, they range from 5m B.O.D. to 5m A.O.D., giving a possible maximum thickness of 10m. The carse clays are overlain by discontinuous peat deposits, indicating the final stage of infilling of hollows, to give a boggy area of ground, formed under stable or more probably, regressive marine conditions. The topmost unit, unconformably overlying most of the section, from immediately south of Glebe Quarry to SE of Kirkbride Burn at

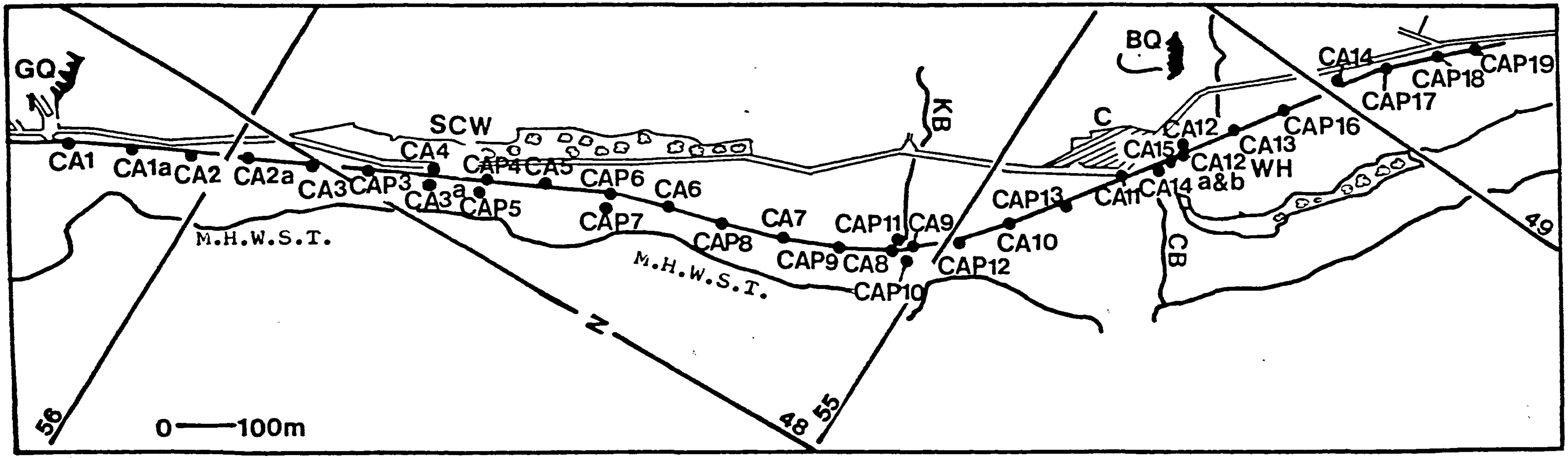


Fig.7.8 Location of boreholes and trial pits, A75 Carsluith By-pass. CA - boreholes, CAP - trial inspection pits GQ - Glebe Quarry, BQ - Bagbie Quarry, SCW - Souter Croft Wood, KB - Kirkbride Burn, CB - Carsluith Burn, C - Carsluith, WH - White Hill

Fig.7.9 Geological section, Glebe Quarry to Carsluith

Scale Horizontal 1:2500 Vertical 1 : 250 (vertical exaggeration 10X)

NX 4851 5492, consists of an approximately 1.25m to 1.50m thick layer of shelly sand, developed during a constructional phase of estuarine beach development in the course of marine regression (see Chapter 7.4, 7.5). The overlying soil profile is largely sandy containing frequent modern roots and rootlets, except in the areas immediately above the hollows occupied by the carse clay. The soil is often clayey and/or peaty, with roots.

7.7 FACIES DESCRIPTION AND STRATIGRAPHY

7.7.1 The solid geology

Bedrock was encountered and penetrated at the base of two boreholes and three trial pits, adjacent to the Carsluith Burn (CA12a+b) and to the SE of White Hill (CA14, CAP17-CAP19). Because of the presence of rock or a large boulder struck at the bottom of CA13, it is estimated also that the rock floor is very close to the base of CA13, and CAP16 on the east side of White Hill. The course of the Carsluith Burn reflects local bedrock geology, in that it flows along the southern junction of the Carsluith granite and its adjacent country rock; erosion was along the zone of weakness at the contact. The granite penetrated by boreholes adjacent to Carsluith Burn was slightly weathered, varying from pale to strong pinkish white in colour, and having steeply-dipping joints. The position of the granite margin was estimated by projection of geological boundaries from the B.G.S. geological map of the area. The margins of the flanking aureole of contact metamorphism were established in a similar manner. SE of White Hill, the bedrock consists of near-vertical to very steeply, NW dipping, cleaved greywackes and siltstones.

7.7.2 The unconsolidated deposits

The unconsolidated deposits are divisible into glacial and post-glacial sediments.

7.7.2.1 Glacial deposits

The two types of glacial deposit encountered were till and fluvio-glacial sand and gravel outwash. The latter is the more widespread, forming marginal kame terraces. The deposits are distributed along the section throughout three easily-distinguished areas.

Locations CA1 to CAP3

At the NW end of the section, the ground level drops from over 10m A.O.D. between CA1 and CA1a, to a little over 5m A.O.D. at CAP3. Between these boreholes, approximately 5m of poorly-sorted, coarse to fine gravels and sands overlie a grey silty clay layer (present between CA2 and CAP3), which contains coarse to fine gravel. The grey silty clay with gravel, cobbles and shells from 1.39m to 4.29m A.O.D. in CAP3, possibly represents glacial till.

Locations CA4 to CA6

Between CA4 and CA6, ground level varies little from 5m A.O.D. The deposits consist of poorly-sorted fluvio-glacial sands and gravels, with cobbles, and in two of the boreholes (CA4 and CAP4), boulders of c. 1m diameter. The true thickness of these deposits cannot be estimated, since their junction with the underlying till (if present) was not recorded. It is envisaged, however, that this surface of contact dips south or south-east between CAP3 (where it was recorded) and CA4. The boundary between the fluvio-glacial and overlying non-glacial deposits forms a hollow, later infilled by carse clays.

Locations CAP13 to CAP19

The most widespread "glacial" material is found at the SE end of the section, where the ground rises from 10.90m to 24.32m A.O.D. but is at its highest on the "summit" of White Hill (27.90m A.O.D.). The fluvio-glacial deposits rest directly on bedrock, without intervening till deposits. Between CAP13 and CA11 the deposits constitute highly compacted, generally variably graded units, of poorly-sorted sands and gravels with frequent boulders. Silt and clay form the matrix, but are not found in great quantity. The Carsluith Burn has eroded a deep channel into the NW flank of White Hill as a result of rapidly falling sea-level in recent times. The boreholes immediately adjacent to the Burn (CAP14 to CAP15), show a fining-upwards sequence, evidence of repeated fluvial re-sorting of the fluvio-glacial outwash. SE of the Burn, the boulder-free deposits immediately underlying White Hill (CA13 and CAP16), consist of well-graded, coarsening-upwards units of silty coarse-to-fine sand and gravel. From CA14 to CAP19, the fluvio-glacial gravel layer thins to c. 0.50m. It rests directly on moderately-weathered, slightly metamorphosed grey siltstones, which contain occasional quartz veins.

7.7.3 Post-glacial deposits

The post-glacial sediments are "carse clays", deposited unconformably by estuarine processes, within what appear in section (Fig. 7.9) as distinct hollows in the fluvio-glacial surface. In three dimensions, there may be only one hollow but, for the purpose of this discussion, the two that appear in the section are treated as separate hollows.

Hollow 1, CAP5 to CAP6

A shallow, asymmetrical hollow is present in the fluvio-glacial deposits between these boreholes, its deepest point probably occurring below CAP6 at c. 0.00m A.O.D. On the flanks of the hollow between CAP4 and CAP5, a thin discontinuous layer of peat rests directly on the glacial deposits. It exhibits numerous roots and becomes sandier with depth. The lower peaty deposits in CA5 may represent reworked sediments from "up-slope" since they are present within a shelly sand and gravel. The latter is probably reworked from underlying sediments.

Evidence for the presence of carse clays is observed in CAP6, where 1.50m of grey, sandy, silty clay with gravel and shells (between 1.89m and 3.39m A.O.D.) rests upon a layer of brown, slightly-gravelly, silty fine sand. It is probable that the lowest sand unit floors the hollow and can be considered a "basal transgressive sand". Overlying the clays at above 3.00m A.O.D. in CAP6 and at 3.50m A.O.D. in CA5, is a loosely-packed black peat, incorporated within a shelly silty sand. The presence of this peat seems to indicate a temporary interruption in marine conditions to give a boggy hollow where peat could form. At the SE end of the hollow, the carse clays are overlapped (and pinched out) by an overlying shelly sand, which rests unconformably and directly on fluvio-glacial deposits.

Hollow 2, CA6 to CA10

The hollow developed between these boreholes is deeper than Hollow 1. A floor of fluvio-glacial material was not reached by the boreholes and pits, but probably is present at depth, falling southwards from CA6. The thickness of the carse deposits cannot be estimated accurately. Between boreholes CA6 and CA10 the carse deposits consist of typical grey to grey-blue, firm to soft clays, interbedded with thin layers of silt and fine to medium sand and occasional gravel layers. The clays have been greatly modified by the shifting channel of the Kirkbride Burn. At CA7, and Kirkbride Burn (CA8, CA9, CAP10 and CAP11), there are several cycles of channel-infill deposits, showing a coarsening-upward sequence of channel floor gravels, silty clays, alluvial gravels. Overlying the carse clays in CAP9 and CAP10 are soft brown clays with shells, thought to represent upper tidal-flat conditions of sedimentation. Peat extends from CAP12 towards CA10, capping the carse clays between these boreholes. The maximum altitude of the upper surface of the carse deposits is estimated as 10m A.O.D. In Fig. 7.9, therefore, the boundary between the hollow and the glacial deposits (from CAP13 southeastwards), is placed at 10m A.O.D. and it is extended northwestwards until it encounters the tentatively calculated position of bedrock. The carse deposits of borehole CA10 are probably in close proximity to fluvio-glacial material as they contain a higher proportion of reworked gravel than the corresponding deposits in the boreholes to the north-west of CA10.

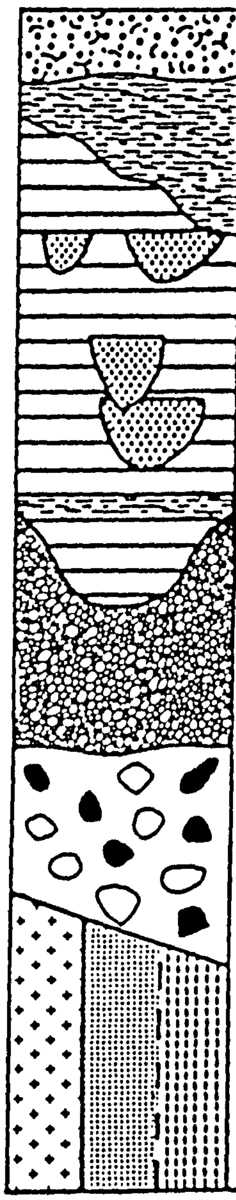
Locations CA2a to CA10

The topmost unit in these boreholes is a widespread, shelly sand blanket resting unconformably on all older deposits and averaging 0.70m in thickness. It is an ill-sorted, largely fine to medium sand with variable silt and clay content and some gravel. It also contains rootlets in its topmost part. The shell/sand blanket is highly undulatory, appearing ridged in the vicinity of CAP6 and CAP7. This ridge is comparable with a ridge at Hollanbank (NX 482 555), where shells of Cerastoderma edule, obtained from the crest of the ridge, at 5.24m A.O.D., were dated at 2,027 ± 108 years by Jardine (1975; Chapter 7.5).

7.8 STRATIGRAPHIC HISTORY AND INTERPRETATION OF THE A75 CARSLUITH BY-PASS IN RELATION TO EUSTATIC/ ISOSTATIC CHANGES

A summarised stratigraphical/environmental column is shown in Fig. 7.10. The till and overlying fluvio-glacial outwash sediments were deposited when the level of the sea was much lower than that of the present-day. The till (CA1 to CAP3) was deposited under conditions of ice advance. When the climate ameliorated, ablation of the ice released large quantities of meltwater and the Cree valley was choked with fluvio-glacial debris, rapidly "dumped" and clearly represented in the section as "moundy" deposits on the underlying till (see CA1 to CA2, CA4 and CA6). The upper surface of the outwash sediments is hollowed between CA5 and CA6, the hollow possibly being a kettle hole. SE of CA6 the fluvio-glacial sediments underlie the carse clays.

Between CAP13 and CAP19, the fluvio-glacial deposits resting on bedrock are terraced, possibly as a result of changing eustatic/isostatic conditions. At CAP19 where bedrock is exposed, the small cliff that is present perhaps was eroded during a period of high relative sea-level prior to late-Devensian times. At the maximum of the last (Devensian) major glacial episode, c. 20,000 - 18,000 years BP, sea-level



Lithology	Environment	Relative movements of land/sea level
Fine to medium shelly sand	Estuarine beach veneer	Continued regression and isostatic recovery to the present day
u/c Clays and peaty layers, roots and fine sands	Peaty marsh / Upper intertidal flat	
u/c Interbedded silts, clays, sands and some gravel. Hollow infill: clays, sands and peat	Gullied channels of meandering creeks in lower tidal flat / Hollow infill in fluvio-glacial surface	Rapid isostatic recovery, sea-level falls (REGRESSION) — Shortlived transgression and increasing isostatic rebound
u/c Fluvio-glacial sands and gravels	Fluvio-glacial marginal kame terraces	Low, but rising, sea-level (TRANSGRESSION)
u/c Till	Glacial conditions, advancing ice	Sea-level at its lowest, land depressed by weight of ice
u/c Granite, metamorphic aureole and Silurian siltstones	"Basement"	

Fig.7.10 Summary of lithofacies and environments in relation to eustatic/isostatic changes

stood at a position much lower than that of the present-day. In Holocene times, sea-level rose again, and the carse clays of this area were deposited in the course of the resulting marine transgression. The time gap at the fluvio-glacial/ carse clay boundary, therefore, is quite considerable; long enough for peat to form on the floor of the hollows between CAP5 and CA5. A small cliff was eroded in the fluvio-glacial deposits between CA10 and CAP13, the sands and gravels of the outwash sediments being incorporated into the carse clays of CA10.

In response to the Holocene marine transgression, the Kirkbride Burn was transformed into a meandering tidal creek, shifting laterally at 90° across horizontally-deposited lower tidal-flats (analogous to the present-day Moneypool Burn at Creetown, Chapter 10). Evidence of lateral channel migration is preserved in three sequences of channel-infill below the present-day Kirkbride Burn, and in a small gully infill at CA7. Below the Burn, the oldest and deepest channel-infill is recorded in CA8, where channel-floor gravels, found at 5.01m B.O.D., are overlain by clayey silts to 0.01m B.O.D. Overlying the silts at the level of O.D. are gravels, deposited during a late phase of aggradation by Kirkbride Burn. The Burn underwent NW lateral migration, resulting in lateral accretion of low tidal-flats in the same direction. The marsh observed in CAP12 probably built out NW, contemporaneously with formation of the tidal-flats. Upper tidal-flats exhibiting a patchy distribution are confined to CA10 and CAP9. During the phase responsible for the third channel-infill, Kirkbride Burn migrated in a SE direction, eroding the clays previously deposited as it moved NW.

Shortly after Kirkbride Burn began migrating SE, marine regression commenced, relative sea-level falling comparatively rapidly. Consequently, the channel-infill in CA8, CA9, CAP11 and CAP10 became of coarser grade as the Kirkbride Burn eroded more vigorously to keep pace with falling sea-level. A temporary halt in the recession of the sea then occurred, resulting in a change of environment. Unconformably overlying most of the section from CA2a to CA10 is a shelly sand, interpreted as an estuarine beach sand, that formed an uneven ridged blanket. This deposit was formed as a result of temporary shifts in estuarine current patterns, that led to shoreward migration and coalescence of shore-parallel bars. Hydrodynamic changes associated with falling sea-level may have been accompanied by meteorological changes that included a dominant SW wind, aiding accretion of the parallel ridges under storm conditions. This constructional phase of deposition is recognised elsewhere on the eastern side of the Cree estuary, e.g. at Cassencarie (see Chapter 7.4 for further discussion), prior to a further fall in sea-level to its present-day position.

CHAPTER 8 - HISTORICAL AND PALAEOGEOGRAPHICAL RECONSTRUCTION OF THE LOWER CREE ESTUARY AREA IN RELATION TO SEA-LEVEL CHANGE

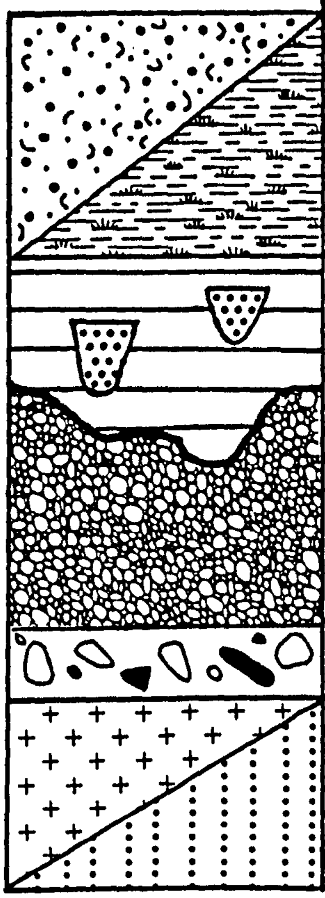
The sedimentary and stratigraphic sequence of the lower Cree estuary area is summarised by a "type" sequence presented in Figure 8.1. The sequence is complete at Cassencarie and Carsluith but the "estuarine beach development" phase is absent from the Creetown area.

The development of the sequence and associated environment within the context of sea-level change at the three locations is now discussed in detail.

Prior to glaciation, sea-level was at least 28m lower than at present since bedrock weathering effects were noted at this altitude (i.e. 28m below the surface at Moneypool Burn), indicating that the area around Creetown was subaerially exposed (see Chapter 7.2.1). It is assumed that sea-level remained low throughout the course of glaciation.

The bedrock surface in the lower Cree estuary area is undulatory or slopes downwards in a general N to S and seaward direction. Upon this surface, at the close of the Devensian age, the fluvio-glacial sands and gravels were deposited during a period of ice ablation (Fig. 8.2). Sea-level was low at this time, but had started to rise. Fluvio-glacial deposits form mound or terrace-like features (e.g. fluvio-glacial kame terraces of Cassencarie and White Hill, Carsluith). Thick (17m) fluvio-glacial sands and gravels infill the palaeovalley of the Moneypool Burn, these deposits probably accumulating rapidly.

The pace of sea-level rise quickened during the early post-glacial period with the advent of the Holocene marine transgression. The sea penetrated northwards from Wigtown Bay flooding into the lower Cree estuary area, initiating a



Lithology	Environment
Shelly sands Silts, clays, fine sands and peat	Estuarine beach, spit, bars Marsh
Interbedded silts, clays, sands and some gravel - known as the "carse clays"	Hollow infill with intertidal flat development and gullied channels
Fluvio-glacial sands and gravels	Fluvio-glacial marginal kame terraces
Till	Glacial conditions advancing ice
Granite Silurian siltstones	"Basement"

Fig.8.1 Summary "type" sequence for the lower Cree estuary area

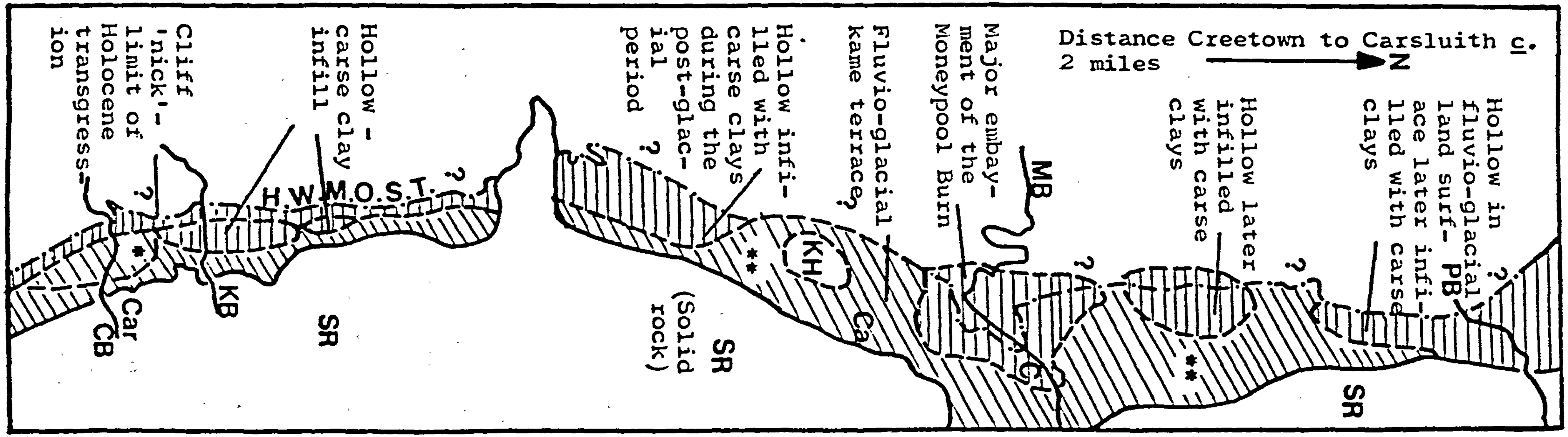


Fig.8.2 Palaeogeography of the lower Cree estuary area, late Devensian to early post-glacial period. PB - Pulwhat Burn, MB - Moneypool Burn, C - Creetown, Ca - Cassencarie, KH - Kettle hole, KB - Kirkbride Burn, Car - Carsluith, CB - Carsluith Burn, H.W.M.O.S.T. - High Water Mark Ordinary Spring Tides, ? - Westerly limits of terraces & hollows uncertain - extended as far as present-day H.W.M.O.S.T. - Limits may have extended further west in the late Devensian and post-glacial period, * - White Hill, thick, moundy deposits overlying solid rock, ** - Fluvio-glacial deposits overlying bedrock

drastic change of environment and style of deposition.

Initially the marine waters flooded the lower courses of the Moneypool, Kirkbride and Carsluith Burns. Small amounts of transgressive coarse-grade lag deposits were reworked from the underlying fluvio-glacial sands and gravels. The sea continued to rise, flooding hollows within the moundy fluvio-glacial deposits (Fig. 8.2), depositing pockets of clays, silts, fine sands and peaty debris unconformably on the underlying sediments. The seaward limit of the hollows is uncertain since the carse clays extending to below present-day L.W.M.O.S.T. are overlain by recent sediments and, therefore, cannot be investigated thoroughly.

Initially the environment was one of lower tidal-flat which gave way to accumulation of upper tidal-flat and marsh deposits as the transgression diminished. The transgressive event itself was shortlived. The sediments deposited were at the "feather edge" of the transgression - as soon as the latter had reached its lateral and altitudinal extent marine waters began to recede. Isostatic rebound started to outpace the rising sea-level and a depositional regression occurred.

North of Creetown and Moneypool Burn the hollows are infilled with upper tidal-flat deposits overlain by marsh (Fig. 8.3). Lower tidal-flat conditions probably did not exist along this margin as far north as these locations. Between the hollows, thin marsh rests directly on fluvio-glacial deposits.

In the vicinity of Creetown there existed a sheltered muddy embayment, protected by the Cassencarie glacial kame terrace. Lower tidal-flats were overlain unconformably by upper tidal-flat deposits and thin marsh. Frequently, upper tidal-flats rest unconformably on older deposits giving rise to numerous erosive breaks. Sediments of the sheltered embayment were dissected by the laterally migrating Moneypool Burn, which

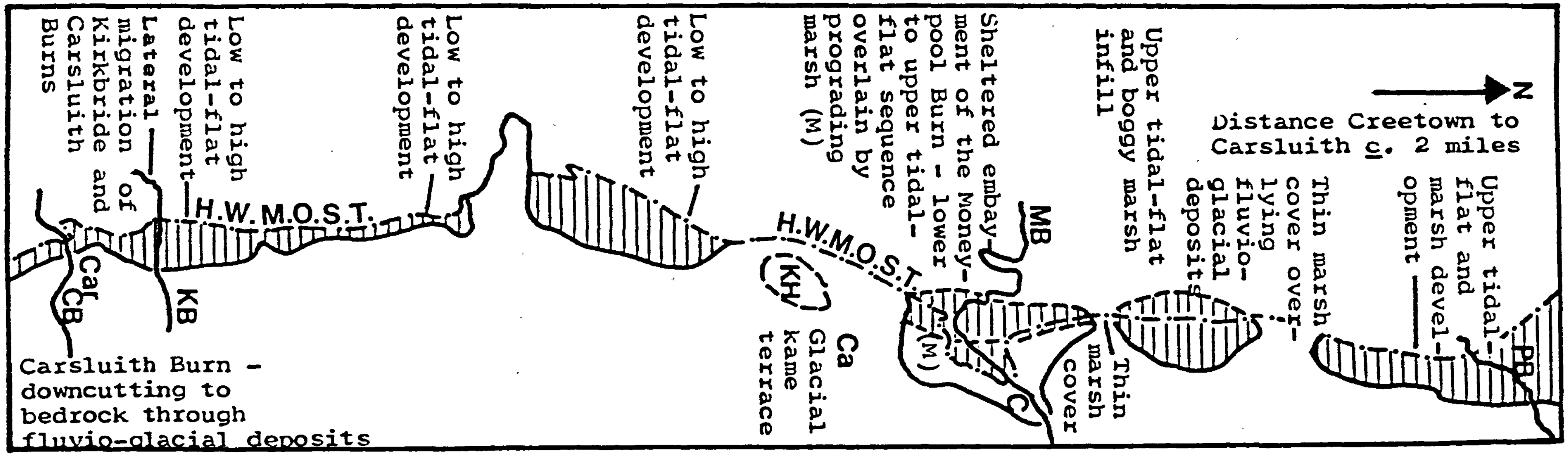


Fig.8.3 Palaeogeography of the lower Cree estuary area, mid post-glacial to c. 2,000 years B.P. PB - Pulwhat Burn, MB - Moneypool Burn, C - Creetown, Ca - Cassencarie, KH - Kettle hole, KB - Kirkbride Burn, Car - Carsluith, CB - Carsluith Burn, H.W.M.O.S.T. - High Water Mark Ordinary Spring Tides

began to incise the carse deposits as sea-level fell. Marsh and tidal-flat progradation occurred simultaneously.

South of Cassencarie as far as Carsluith, similar environmental conditions to those of the Moneypool Burn existed. The Kirkbride and Carsluith Burns underwent several phases of lateral migration. As sea-level fell, patches of peat accumulated at the base of the cliff beneath White Hill. The Carsluith Burn downcut vigorously to bedrock through fluvio-glacial deposits.

The depositional regression led to the seaward progradation of intertidal flats and marshes. Increased incision occurred as the River Cree kept pace with the rapid withdrawal of the sea.

Certain morphological features of the Cassencarie area are the result of a pause in the Holocene marine regression c. 2,000 years B.P. The pause coincided with changing meteorological conditions. Stormy conditions resulted in the reworking of the kame terrace deposits at Cassencarie to form a spit (Fig. 8.4). The terrace was breached at a low point and an existing kettle hole was flooded by the sea. Simultaneously, to the south, medium- to coarse-grade marine sediments (sands and gravels) and reworked fluvio-glacial deposits were transported landwards to form shore-parallel and oblique bars. These are localised features developed between Cassencarie and Carsluith, preserved as ridges seen in aerial photographs. No evidence of the presence of bars was found at Creetown or further north, due probably to its sheltered location. In the vicinity of Carsluith similarly-derived material forms a thinly-developed estuarine beach blanket.

Since 2,000 years B.P., the sea has receded further. To the north of Creetown a marsh environment is present around H.W.M.O.S.T. To the south of Creetown below H.W.M.O.S.T.,

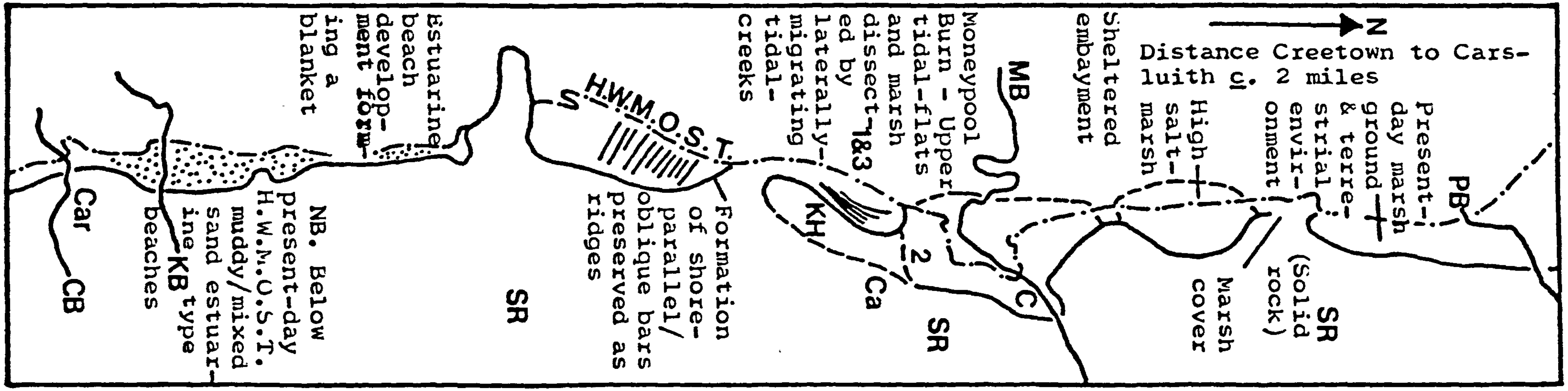


Fig.8.4 Palaeogeography of the lower Cree estuary area c. 2,000 years B.P. to the present day. PB - Pulwhat Burn, MB - Moneypool Burn, C - Creetown, Ca - Cassencarie, KH - Kettle hole, KB - Kirkbride Burn, Car - Carsluith, CB - Carsluith Burn, H.W.M.O.S.T. - High Water Mark Ordinary Spring Tides. Effects of pause in Regression:- 1 & 3. Reworking of kame terraces & spit construction, 2. Breaching of terrace at low point & flooding of kettle hole.

the environment is of mud or mixed sand/mud estuarine type beaches. At present, the shores of the Cree estuary show a mixture of erosive and depositional features. South of Creetown as far as Carsluith, H.W.M.O.S.T. is marked by a small cliff c. 1m in height and backed by a supratidal grassy backshore. Elsewhere it is located on a depositional feature, e.g. a prograding mudbank.

CHAPTER 9 - THE UPPER FLEET ESTUARY SECTION

9.1 THE A75 GATEHOUSE-OF-FLEET BY-PASS SECTION

9.1.1 Introduction

A correlated NW to SE geological section, assembled from borehole information acquired by Babtie Shaw & Morton during a preliminary survey along the line of the proposed A75 diversion, south of Gatehouse-of-Fleet (Fig. 9.1, Inset), has yielded valuable information regarding the nature and history of the valley infill at this point. A total of eighteen boreholes and one trial pit were recorded in the section (Fig. 9.1), which is now discussed.

9.2 FACIES DESCRIPTION AND STRATIGRAPHY

9.2.1 The solid geology

The "palaeovalley" floor of the Water of Fleet (as defined by the solid rock/drift junction) exhibits a 2.5km wide "U"-shaped cross-sectional profile, characteristic of an area which has been scoured by ice, which in this region moved from NNE to SSW, perpendicular to the cross section. The valley floor is asymmetrical, its deepest point c. 27.50m B.O.D., below BO55, SE of Cardoness Bridge. The rocks underlying the section consist of green-grey greywacke sandstones, dipping steeply or vertically to the NW. The sandstones are cut by numerous quartz veins and quartz-filled tension gashes.

9.2.2 ? Glacial till/Fluvio-glacial sands and gravels

The till, averaging 3m in thickness, recorded in the extreme SE of the section, rests directly on the rock floor of the valley side. The deposits comprise an upward-coarsening sequence of clayey silts, with brown, fine to coarse sub-rounded cobbles, overlain by alternations of brown silt and coarse sand with fine to coarse sub-angular to sub-rounded gravel.

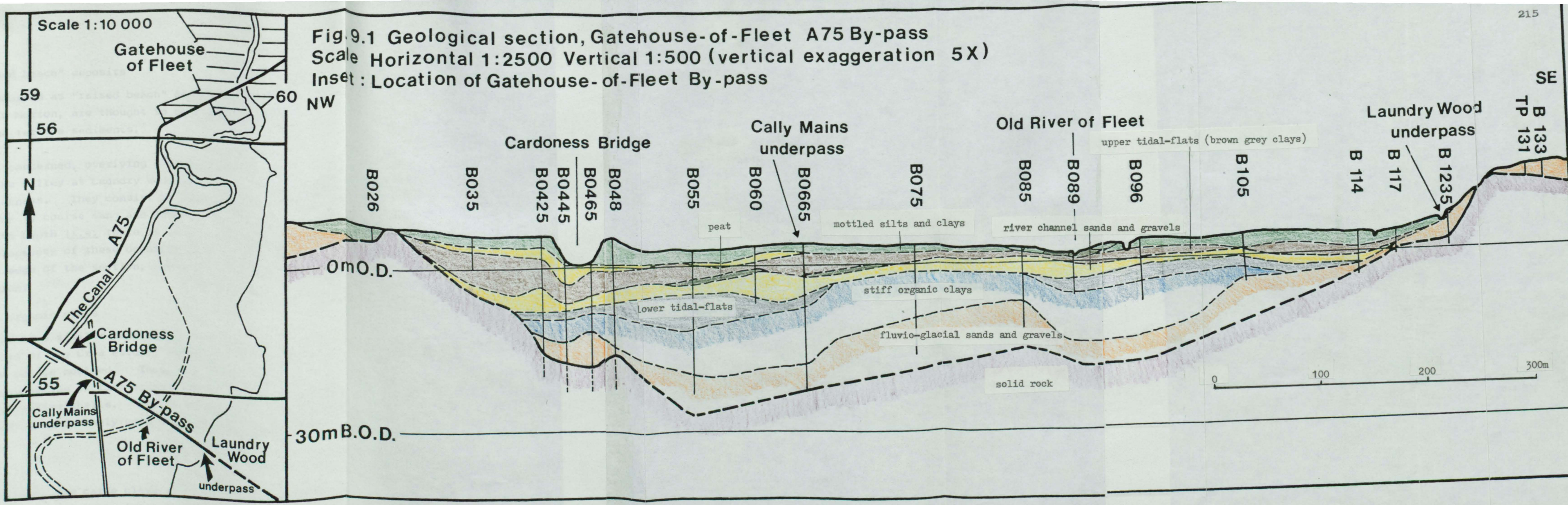


Fig 9.1 Geological section, Gatehouse-of-Fleet A75 By-pass
Scale Horizontal 1:2500 Vertical 1:500 (vertical exaggeration 5X)
Inset : Location of Gatehouse-of-Fleet By-pass

9.2.3 "Raised beach" deposits

Sediments recorded as "raised beach" deposits by B.G.S. and Babtie Shaw & Morton, are thought to be fluvio-glacial marginal kame terrace sediments.

The deposits concerned, overlying a rock bench located on the SE side of the valley at Laundry Wood (B1235), vary from 3.50 to 4m in thickness. They consist of well-sorted, alternating layers of fine to coarse sand and cobbles. Sand content increases with depth (i.e. there is an upward coarsening). Thicker developments of these deposits are recorded NW of B026, on the edge of the section, but are not considered in this discussion.

9.2.4 Stiff organic clays

These deposits have similar textural characteristics to the pale grey clays of the Cree estuary (Chapter 5), i.e. they are stiff and can be moulded. These clays also contain a significant proportion of fine organic material, but there is no evidence of marine shells. The stiff clays, 9 to 10m in thickness, rest unconformably upon the underlying sands and gravels.

9.2.5 Carse clays

The contact between the carse clays and the underlying stiff clays is assumed to be an erosional disconformity as in the Cree valley area. The carse clays are overlain unconformably by river-channel gravels and sands. The grey clays vary from 2.50m to 6m in thickness, consisting of laminated, grey, clayey sandy silts, with an increasing clay content with depth. They contain plentiful shell fragments, suggesting that the facies was formed under marine/estuarine conditions, or had connections with a marine environment.

9.2.6 River-channel gravels and sands

These deposits are generally poorly sorted, sheet-like gravels and sands, varying from 1.50 to 5m in thickness, contained within channels downcut into estuarine/tidal-flat sediments. The lower unit of channel gravels and sands spans the whole width of the valley, overlapping slightly onto the "raised beach" deposits in the SE, and solid rock in the NW. Between Cally Mains underpass and the Old River of Fleet, the lower unit of river gravels and sands rests on a stiff grey clay "mound", the surface of the mound having been levelled by erosion as the channel swept across the valley. It should be noted that this mound was a prominent feature with a hollow containing carse clays on either side. The facies is repeated between Cally Mains underpass and the NW margin of the Fleet valley, being emplaced within the brown-grey clays. It varies from 2 to 5m in thickness.

9.2.7 Peat

The lower unit of river gravels and sands is overlain at two localities, NE and SE of Cally Mains underpass, by peat approximately 0.50m to 1m in thickness. In the section (Fig. 9.1), two separate lenses of peat are shown. It is possible, however, that the lenses represent a continuous, more extensive thin layer of peat. Peat is also forming at the present-day surface of the Old River of Fleet infill.

9.2.8 Brown-grey organic clays

These soft clays, 2 to 3m thick, and overlying the lower unit of river-channel gravels and sands unconformably, comprise brownish-grey laminated clays, with variable amounts of organic matter. They overlap the limits of the river deposits to rest on "raised beach" material in the SE and solid rock in the NW.

9.2.9 Mottled silts and clays with rootlets

These silts and clays blanket all older facies unconformably, overlapping and resting directly on "raised beach" deposits in the SE and on solid rock and raised beach deposits in the NW. The deposits are soft, mottled grey-brown, orange-brown, clayey silts and clays penetrated by rootlets, with traces of organic matter, and scattered pockets of fine to medium sand.

The Old River of Fleet

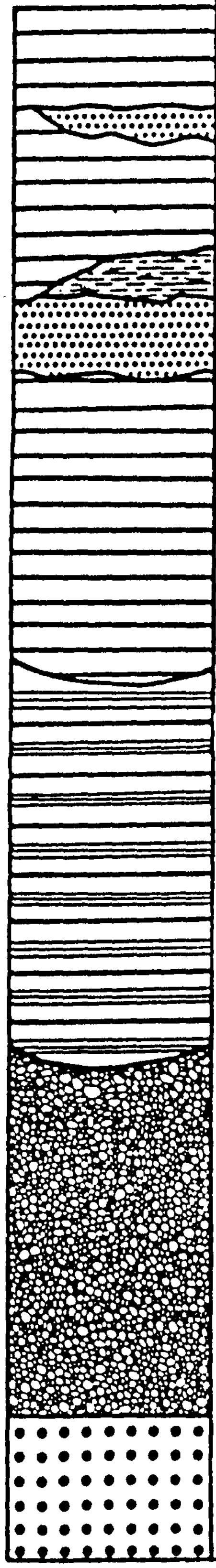
The course of the Old River of Fleet consists of a repeat of the afore-described facies, resting on the brown-grey organic clays, perhaps within an erosion channel. The muddy infill contains a few shell fragments, together with peat which is still forming at the present day.

9.3 STRATIGRAPHIC HISTORY AND INTERPRETATION OF THE GATEHOUSE-OF-FLEET SECTION IN RELATION TO EUSTATIC/ISOSTATIC CHANGES

A summary of the lithofacies, interpreted environments and chronology of events is presented in Figure 9.2. During the last main Devensian glaciation, the Gatehouse-of-Fleet area was scoured by ice originating in the hills to the north (Geol. Survey Sheet 5 Explanation). Direction of ice travel was N to S and NE to SW, as indicated by striae recorded on roches moutonées. The ice probably moved in a NE to SW direction down the Fleet valley, depositing the till recorded at the SE margin, on the bare rock floor.

When climatic conditions ameliorated and the ice melted, a blanket of fluvio-glacial sand and gravel outwash was deposited on the floor and margins of the Fleet valley. Sea-level was lower than at present, but rising during this time.

Overlying the fluvio-glacial deposits unconformably are "stiff" organic clays, possibly deposited in a boggy marsh environment. Since the clays are very similar to the pale grey clays of the Cree valley, which are thought to be estuarine and/or marginally terrestrial in nature, it is further suggested that with time the waters of the boggy marsh environment in the Fleet valley became increasingly saline and eventually fully estuarine/ marine in character. The transition from the stiff organic clays to the overlying shelly grey clays corresponds with a transgression as the sea penetrated the area, transforming it into an estuary. A lower tidal-flat environment was established, with typical



Lithofacies	Environment	Relative movements of land/sea level
Mottled silts & clays, rootlets & s. laminae	Marsh Upper tidal-flat	Regression to present-day REGRESSION
u/c Gravels & sands, clays & silts, s. laminae	Upper tidal-flat with fluvial channels	
u/c Peat lenses	above H.W.M.O.S.T. ?	?
u/c Gravels & sands u/c Laminated clayey, sandy silts & grey clays, abundant shell fragments	Lower tidal-flat with fluvial channels	Continued transgression (? slowing due to now increased isostatic rebound)
u/c "Stiff", organic (? pale grey) clays, with abundant, scattered organic matter	High tidal-flat or boggy marsh	Rapid transgression TRANSGRESSION
u/c Fluvio-glacial sands & gravels	Fluvio-glacial outwash plain, marginal kame terraces	Low, but rising sea-level
u/c Silurian greywacke sandstones	"Basement"	

Fig.9.2 Summary of lithofacies and environments in relation to eustatic/isostatic changes. u/c denotes the presence of an unconformity, s. laminae denotes the presence of sand laminae

horizontally-bedded deposition occurring through the processes of lateral migration of muddy point bars of the "palaeo-Fleet".

Estuarine conditons persisted for a short time only, prior to the deposition of extensive river-channel gravels and sands of the "palaeo-Fleet". These sediments are interpreted as deposits of a laterally-migrating, low-sinuosity river-channel (hence their sheet-like nature), which swept across the Fleet valley in a NW to SE direction. The channel deposits represent a period of fluvial dominance, due to the now-increasing isostatic rebound, that resulted in increased erosion rates and fluvial aggradation. Limited evidence for a minor regression at this time is available in that a thin layer of peat, perhaps as two separate lenses, is recorded as overlying the channel gravels. This may suggest that sea-level had dropped low enough for peat-forming conditions to develop. However, it is just as possible, and more probable that peat-forming conditons developed in relation to a change in river-channel position due to avulsion processes.

The overlying soft, brownish-grey clays are interpreted as muddy upper intertidal flat deposits, with variable amounts of washed-in organic matter. It is suggested that the peat did not form under conditions of regression, but did so in an environment above H.W.M.S.T., under rising sea-level conditions. The thickness of the peat can be accounted for by rapid growth, which initially outpaced the rate of sea-level rise. The latter diminished as the sea reached its maximum altitudinal and lateral extent. The position of the peat relative to the overlying tidal-flat, therefore, can be explained on the basis of the behaviour of adjacent but shifting environments and their lateral relationships as the valley infilled whilst sea-level continued to rise but the rate of rise was diminishing.

It is envisaged that sea-level had started to fall during deposition of the brown-grey organic clays, and this phase was followed by a pulse of fluvial dominance with a further period of channel gravel and sand deposition. At this time, river migration was confined to the NW margin of the valley, west of Cally Mains underpass.

The mottled silts and clays lie unconformably on the soft, brown-grey clays below. SE of Old River of Fleet, erosion of the upper tidal-flats resulted in the mottled silts resting unconformably on older channel deposits; a channelised depression in the marsh was filled subsequently with prograding high intertidal flat to marsh deposits (i.e. the mottled silts and clays).

West of Cally Mains underpass, the clays and silts rest unconformably on river-channel gravels and probably represent the infilling and silting up of a channel, followed by marsh progradation, as avulsion had created a new channel for the Water of Fleet further to the SE. The new channel, which appears to have been tidal, as the sediments contain shell fragments, was infilled with muddy clays. The course of the Old River of Fleet has been altered in historical times, the river being artificially straightened between locations NX 595 557 and NX 588 547. This has led to rapid incision into old river sands and gravels by the channel of the present-day Water of Fleet, since it cannot freely migrate between two concrete walls. The abandoned channel of the Old River of Fleet is infilled with peat deposits which are forming at the present-day marsh surface.

PART B

THE PRESENT-DAY ESTUARY OF THE RIVER CREE: PROCESSES AND PRODUCTS

CHAPTER 10 - THE CREE ESTUARY SYSTEM

10.1 GENERAL INTRODUCTION AND BACKGROUND

An estuary is a particularly ephemeral feature of the earth's surface, located in the transitional zone between terrestrial and marine environments and, therefore, subject to the interactive nature of fluviatile and marine regimes, and longer-term effects of eustatic and isostatic changes. These influences create characteristic estuarine conditions which control erosion, transportation and deposition in a physically complex and varied environment, which is as yet inadequately defined. There have been many attempts at defining an estuary, each dependent on the author's personal point of view, e.g. Davies (1973), Hayes (1975), Berthois (1978) and Fairbridge (1980). The most frequently adopted is that of Pritchard (1967, p.3-5), who stated that an estuary "is a semi-enclosed body of water which has free connections with the open sea and within which sea water is measurably diluted with fresh water derived from land drainage". From a sedimentologist's point of view, however, this definition is too narrow as it does not consider the importance of sedimentary structures and facies. For the purpose of this study, the most appropriate definition is that given by Howard & Frey (1980): "an estuary is a complex of intertidal and shallow sub-tidal, intercoastal facies, dominated by tidal processes, exhibiting conspicuous variations in sediment texture, composition and provenance and in physical and biogenic structures".

The estuary of the River Cree is a tributary estuary of the Solway Firth, aligned at right angles to the Firth's northern shore (Fig. 10.1). The ENE - WSW trending Solway Firth covers an area of 2,560km^2 and is divisible into "inner" and "outer" areas on the basis of hydrographical and biological criteria (Perkins,1973). The estuary under consideration belongs to the "outer" region of the Solway Firth, defined as being west of a NW - SE line from Southerness Point on the

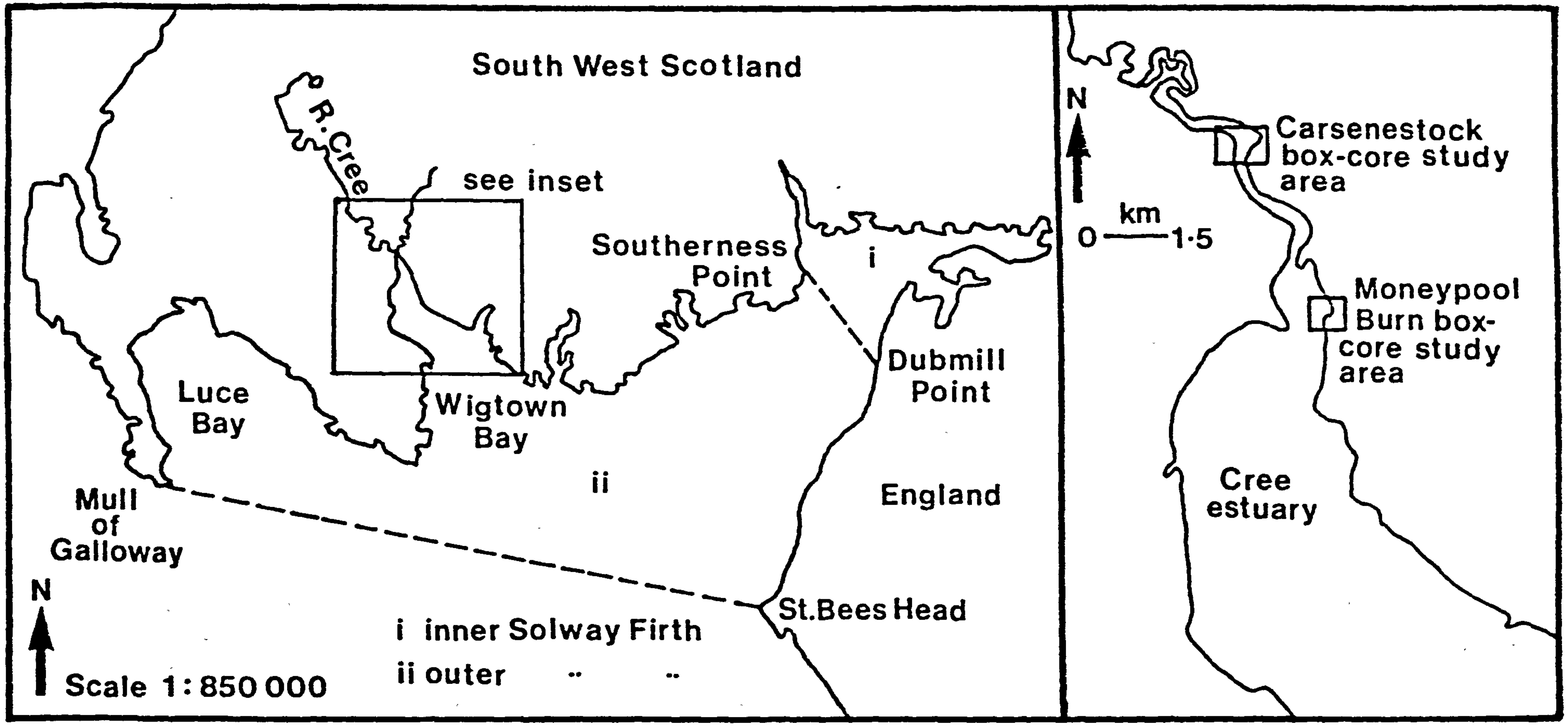


Fig.10.1 Location of the River Cree estuary, Solway Firth, Scotland. Inset : location of box-core study areas

Scottish shore to Dubmill Point, Cumbria (Perkins, 1973 p.30). The outer limit of the Solway Firth is defined by a WNW - ESE line from the Mull of Galloway to St. Bees Head.

In order to understand the estuarine processes operating within the Cree estuary and the resulting pattern of sediment distribution and sedimentary structures of the box-core study areas (Fig. 10.1, inset), it is necessary to outline the distribution, texture and bedforms of sea-bed sediments, and to give a description of tidal-current processes operating in Wigtown Bay and the immediately adjacent part of the Solway Firth. It is envisaged that the Cree estuary receives a considerable sediment input from the adjacent shelf area. This inference is not easily proved, but is hinted at by the prevalence of flood-dominant structures of various sizes, e.g. ebb/flood "avoidance" channels and flood-oriented ripples, within all the box-core study areas, suggesting a persistent shoreward movement of sediment. Once within the estuary "mouth", the sediment input becomes trapped by the flood-dominated processes and, although vigorously reworked by estuarine processes, is progressively carried up-estuary to be deposited (Van Straaten & Kuenen, 1957, 1958 and Postma, 1961, 1967). As a result of the processes involved, there is a distinct separation of muddy and sandier sediments, the former being concentrated in the upper regions of the estuary (north of Creetown), the latter in the form of tidal shoals, south of Creetown towards Wigtown Bay. Because of the high proportion of muddy sediment that is accumulating north of Creetown, the estuary is silting up rapidly.

The "outer" region of the Solway Firth is characterised by varied sea-bed sediments and bedforms (Figs. 10.2a and 10.2b respectively). The greatest distribution of muddy sediments outside the estuary occurs within the Wigtown Bay area, as far south as Burrow Head. Muds are thought to concentrate in the Bay due to the relatively sheltered position for deposition. An approximately concentric pattern of sediments occurs, varying from the centre outwards from mud to sandy mud to

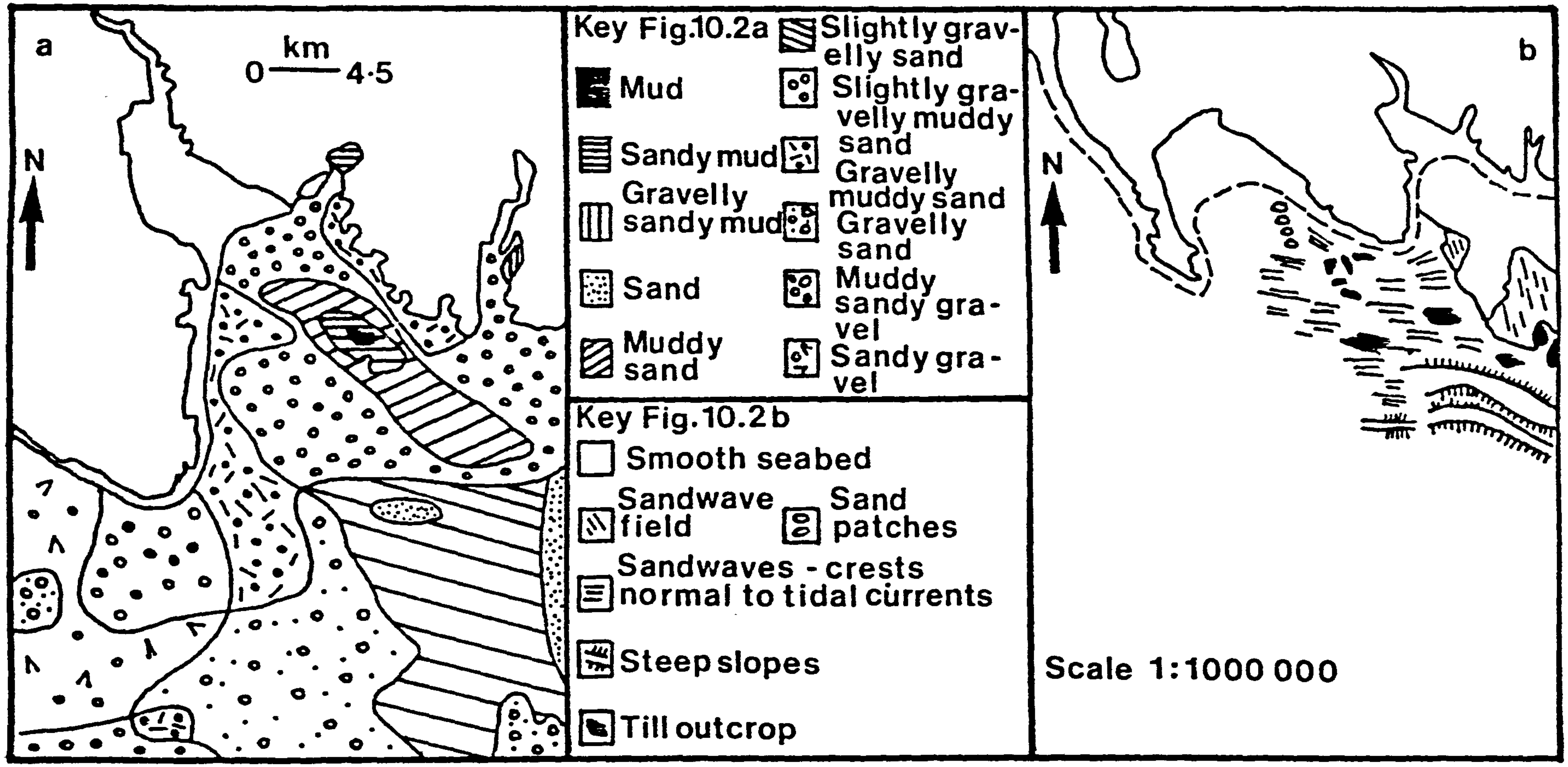


Fig.10.2a Distribution and texture of sea-bed sediments to the south and south-west of the Cree and Fleet estuaries (after BGS 1:250 000 Sea-bed sediments and Quaternary geology Map)
Fig.10.2b Distribution of bedforms on the sea floor (outer Solway Firth), south and south-west of the Cree and Fleet estuaries (after Caston, 1976 and BGS 1:250 000 Sea-bed sediments and Quaternary geology Map)

slightly-gravelly muddy sand and gravelly muddy sand (cf. Folk, 1954). This substantial body of muddy deposits is thought to contribute considerably to the fine-grained sediment within the Cree estuary. Sediment distribution within the Cree estuary indicates an abrupt landward-fining, from predominantly slightly-gravelly muddy sand at the mouth to sandy mud as far north as Creetown in the lower Cree estuary, fining to slightly-sandy silt and mud north of Creetown in the upper Cree estuary.

Immediately SW of Burrow Head there is a distinct coarsening of grain size of material, varying from gravelly muddy sand to gravelly sand to muddy sandy gravel. SE of Burrow Head, the grain size is predominantly slightly gravelly sand with sand patches.

The distribution of bedforms (Fig. 10.2b), as assessed by Caston (1976), corresponds closely with the sediment grain-size distribution and texture. From Wigtown Bay to its confluence with the Solway Firth (area of concentric mud deposition), the sea bed is smooth and featureless, as would be expected in fine-grained muddy sediments. Immediately SW of Burrow Head (in sands and gravels), the sea floor is smooth to gently rounded with a development of gravel furrows aligned parallel to the tidal stream. Extensive sand deposits on a smooth floor SE of Burrow Head are fashioned into sand and gravel waves, with crests aligned at right angles to tidal currents.

Bedform distribution and construction is a product of the specific nature of the available sediment size-grade and the tidal-current processes in operation, which in turn are considerably influenced by prevailing meteorological conditions. Perkins (1973, p.7) states that, during the summer, an onshore movement of sand, deposited by long, low waves, is detectable in the Solway Firth. The reverse occurs in winter, with erosion resulting from the plucking action of short steep waves. Longshore drift is negligible throughout the Solway Firth, possibly because of the intricate nature of the coastline.

In the movement of sediment, tides are of much greater influence than waves in the "outer" Solway Firth. Amplification and asymmetry of the tidal wave as it moves shorewards on to an indented coastline with funnel-shaped estuaries results in a sharp rate of tidal rise and a slower rate of fall. Due to rapid changes in flow direction of tidal currents at low and high water, ebb/flood "avoidance" occurs, a situation where outflowing and inflowing currents follow different courses to produce separate ebb and flood channels. This situation is characteristic of the whole of the Cree estuary, at varying scale, although in the fluviatile part of the estuary, north of Creetown, the ebb/flood avoidance pattern is "weakened" by strengthened fluvial flow.

10.1.1 Tidal dynamics of the Cree estuary

The tidal range of the Cree estuary exceeds 4m. Therefore, according to Hayes (1975), it is classed as a macrotidal estuary. The tidal cycle, lasting approximately 12 hours and 30 minutes, is semi-diurnal. The tidal wave is greatly amplified as it progresses landwards, especially north of Creetown, where the estuary channel is restricted between incised banks. Flooding of the estuary takes approximately 3 hours and 30 minutes, whilst the duration of the ebb flow is 9 hours. Maximum current velocities are offset from the mid-point between ebb and flood tide; maximum ebb velocities occur very early in the ebb period, _c_.30 minutes to 1 hour after high tide, whilst maximum flood velocities are attained over a similar length of time after low tide. The flood current maximum velocities are greater than those of the ebb, but are normally of shorter duration. Asymmetry is also illustrated by relatively low velocity for a longer time near the slack after flood (closer to high water than after ebb); _i.e._ the current direction turns more slowly at high water than at low water.

Meteorological Forces

Variations in wind stress and atmospheric pressure create water-level changes that affect and disrupt the circulation pattern of tidal currents on the shallow sea shelf bordering the estuary. Consequently, tide heights vary considerably as a direct result of the cumulative effects of tide type (neap, spring) and prevailing meteorological conditions. It was observed that the incidence of the flood tide on the Cree estuary would frequently be 30 minutes later than predicted if the waters were retarded in the estuary mouth by an opposing NW wind. If the wind was from a SE direction, the flood tide was usually earlier than anticipated. Ebb flows, on the other hand, were accelerated by NW winds and restrained by south-easterlies. When barometric storm surges are co-incident with a spring tide and a period of heavy rain (the latter usually in winter), a bore forms on the River Cree at Carty Port (NX 4350 6230), due to oversteepening of the already highly asymmetrical tidal wave-form and because of a constriction in river width at this location. The bore travels upstream, steepening at Roadfoot (NX 4350 6580), where it meets further constriction in river width. The bore continues upstream to the NTL, overtopping adjacent banks and flooding the surrounding farmland.

It is very difficult to generalise about meteorological conditions but fair to say that any subtle change affects the tidal dynamics acutely, thereby altering the pattern of sedimentation within the estuary. Since meteorological conditions are highly unstable and variable, it can safely be assumed that the state of sedimentation within the estuary at any given time is also variable and highly complex.

10.1.2 Introduction to sub-environments of the present-day Cree estuary

The River Cree rises in Loch Moan, on the western flank of Merrick, within Galloway Forest Park (Fig. 10.3). Its catchment area overlies an area of Ordovician and Silurian

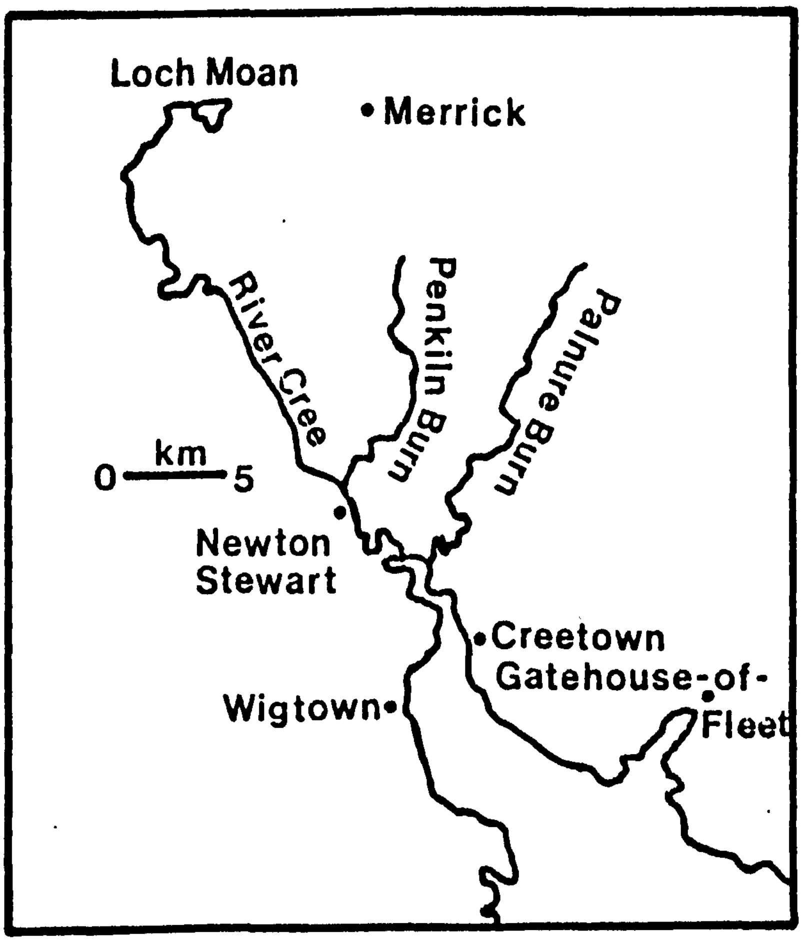


Fig.10.3 Map to show River Cree drainage basin

sediments and younger intrusive rocks, covered by moorland (with peat), deciduous and coniferous forest and part-agricultural land. The annual volume of freshwater entering the estuary from the upper reaches of the Cree (north of Newton Stewart) is constant but peak discharges occur during winter and spring thaws. Additionally, there are occasional "flash floods" due to summer and early autumn storms. The development of the upper Cree drainage system, from its source southwards to Newton Stewart, is discussed by Jardine (1959).

For the purpose of this study, the estuary of the River Cree is defined as extending southwards from the river's normal tidal limit (NTL), at location NX 416 646, for a distance of c. 16.5km, to where it enters Wigtown Bay, south of Carsluith.

The upper Cree estuary (Fig. 3.2), extending from the NTL to Creetown (location NX 470 580), flows in a NNW to SSE direction for a distance of 7.5km. The river is deeply incised and highly sinuous, essentially fluvial in character but nevertheless still strongly influenced by tidal processes. The marked sinuosity is due to active erosion in cohesive bank materials (clays and silts), combined with a steady discharge and recent incision due to lowering of base level upon marine regression, followed by infilling of the estuary.

The Palnure Burn (Fig. 10.3) is an important left bank tributary of the River Cree, flowing N to S through a steep-sided valley confined by rock walls to its confluence with the Cree at location NX 452 652. The valley of the Palnure Burn is divisible into 3 areas as follows:

1. Bargaly Glen (north of Craignine Bridge at location NX 4600 6631) - rock-floored; not considered in the following discussion.
2. Craignine Bridge to the NTL - flat-floored; thinly-developed carse clays resting upon fluvio-glacial deposits.

3. NTL to confluence with the River Cree - the Burn has a sinuous course, with tidal-creeks.

For a distance of over 3km, the Palnure Burn assumes a sinuous course from its NTL near Crew Hole (NX 4577 6527) to its mouth and confluence with the River Cree. At location NX 453 627, there is a well-developed meander known as "the Loop". The Burn is 10m in width at its NTL, reaching 60m in width at its confluence with the River Cree. It experiences flood-tide velocities comparable in rate with those of the River Cree. The flow is highly turbulent, with a considerable amount of clay and silt in suspension. After a period of heavy rain, when fluvial discharges are increased, fresh-water extends as far south as location NX 4588 6438, 0.90km downstream from the NTL. The flood tides do not reach the NTL at these times. The situation equilibrates over a period of days as discharge returns to normal.

The lower Cree estuary (Fig. 3.2), extends from south of Creetown, at location NX 470 580, to the mouth of the estuary, defined as a NE to SW line from Garvellan Rocks (NX 550 514) to Eggerness Point (NX 494 464), a distance of 9km. It is a true estuary, characterised by a frequently-shifting network of channels and tidal-flats (unvegetated), located south and SW of Creetown, respectively. South of Carsluith, the estuary is essentially an inlet with elongate tidal sand banks or ridges, separated by ebb/flood avoidance channels. Extensive intertidal flats flank the western margin of the Cree estuary south of location NX 460 580 as far as Jultock Point (NX 488 490).

Detailed investigations of the sub-environments of the Cree estuary are discussed in Chapter 10.2 and 10.3 respectively.

10.1.3 Methods of investigation

The collection and preservation of sedimentary structures from unconsolidated sediment was achieved by the taking of box-core samples and the making of resin peels. These two methods, described by Collinson & Thompson (1982), are now discussed.

Box coring using the Senckenberg-type box

Straight-sided, open-ended boxes (20cm length x 15cm width x 10cm depth), oriented parallel to the ebb/flood direction, were pushed vertically into the sub-aerially-exposed sediment surface to obtain a cross section of the preserved sedimentary structures. The boxes were then extracted by spade, after the insertion of the box lid or cover to contain the sediment (Fig. 10.4).

Resin Peels

Back in the laboratory, the box-core samples were trimmed, and surfaces were levelled and scraped clean with a razor blade and soft paint brush to enhance sedimentary structures and macrofauna that were present (Fig. 10.5). The contents of the boxes were photographed in black and white and enlarged prints obtained for study. Using a gun method, the samples were then impregnated with an epoxy resin (Ciba-Geigy Araldite EP-IS), which penetrated the sediment to variable depths according to the differing porosities and permeabilities of individual layers (of clay, silt and sand).

After the resin had hardened (in approximately 24 hours), the samples were released from the boxes and the peels cleaned of remaining loose sediment. The contrasting grain size of laminations now stood out in relief. The peels were photographed further, for a comparative study with those taken prior to impregnation and, in addition, so that photography would enhance preserved details of sedimentary structures.

10.2 A STUDY OF LARGE-SCALE BARS AND SMALL-SCALE SEDIMENTARY STRUCTURES IN THE UPPER CREE ESTUARY

10.2.1 Introduction

The incised tidal channel of the River Cree between its NTL

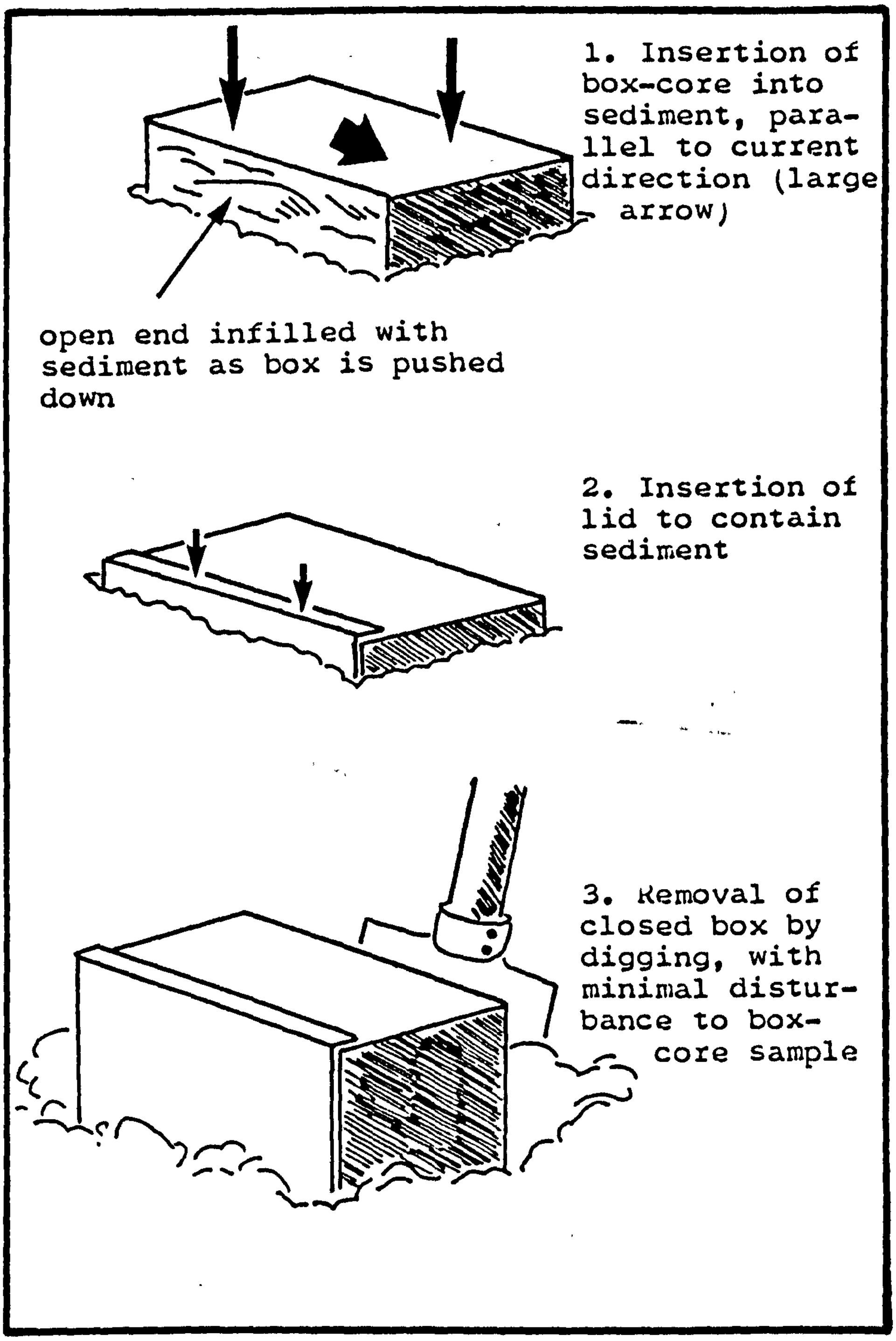


Fig.10.4 Sketches to illustrate method employed in the collection of box-core samples

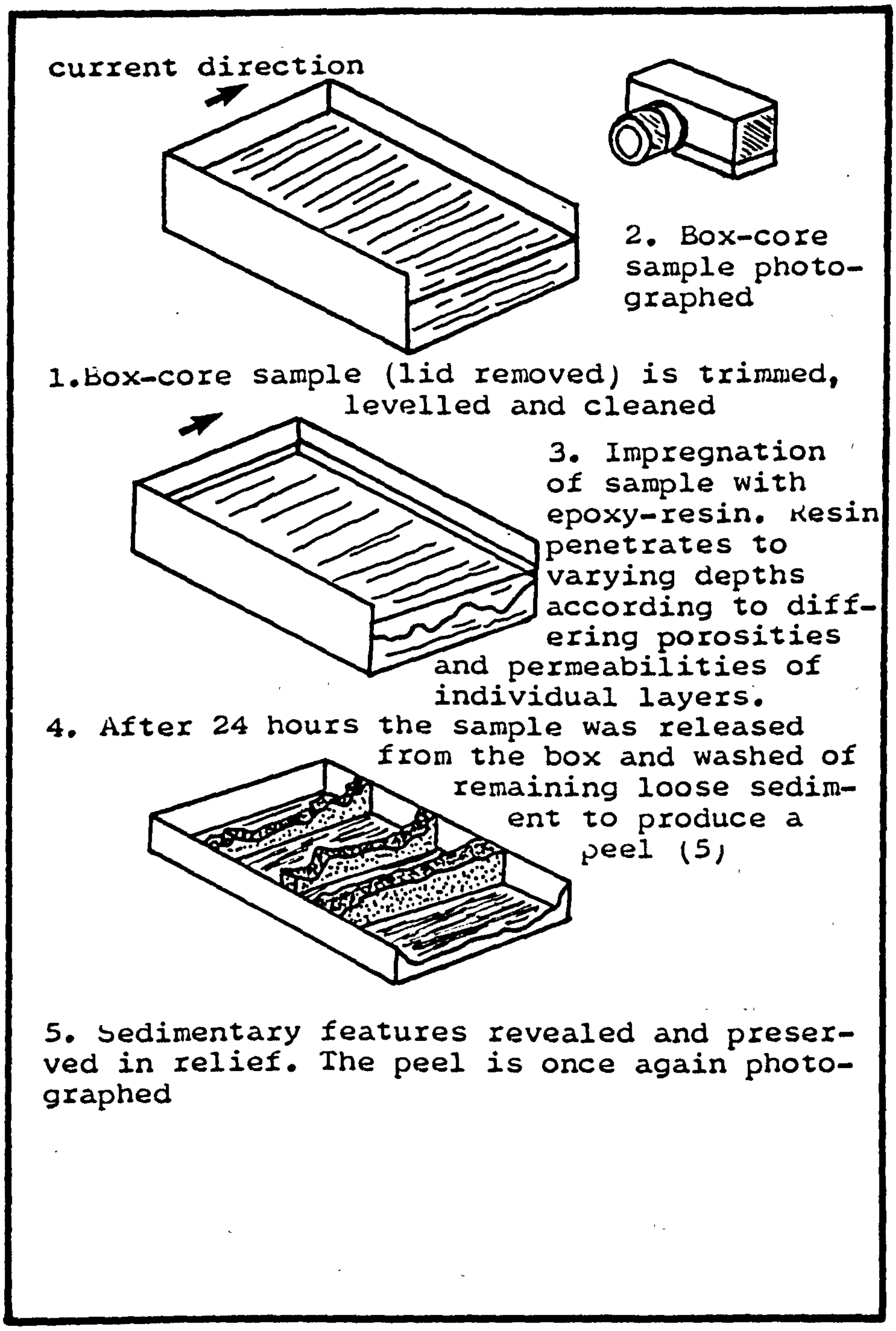


Fig.10.5 Sketches to illustrate method employed in the construction of resin peels

(at NX 416 646) and Carsenestock (NX 445 619) exhibits high flood water stage, bankfull sinuousity but, as the ebb water falls, mid-channel bars, side-bars and point-bars appear, the channel now becoming braided and irregularly anastomosing (Fig. 10.6). Chutes are common across the large point-bars.

Large- and small-scale sedimentary structures are found on exposed bar surfaces along a 1.5km reach of the river between locations NX 441 626 and NX 448 619 (Fig. 10.7). Small-scale structures revealed in box-core samples from the upper Carsenestock point-bar and adjacent chute-channel (Figs. 10.7 and 10.16) exhibit an interplay between fluvial and tidal ebb/flood flow, but prove that, overall, flood-tidal processes dominate.

A stable, channel-floor side-bar at Blackstrand (Fig. 10.7) is composed of unidirectional ebb-oriented dunes with planar, cross-bed foresets in coarse sand. No flood-oriented features were observed, the dunes being constructed wholly by fluvial and ebb-influenced currents.

An opposing alternate side-bar at Carsenestock is also ebb-oriented but with lunate dunes. It merges downstream at location 2ii (Fig. 10.7) with the Carsenestock point-bar. At the same location, there is an interference of ebb- and flood-oriented, lunate dunes. Sedimentary structures of the Carsenestock point-bar, however, are predominantly flood-oriented.

10.2.2 Factors governing the formation and destruction of large- and small-scale sedimentary features

The channel side-bars and the point-bar along the studied reach of the River Cree are highly unstable, their formation and destruction being dependent on changes in tidal dynamics (which occur diurnally and monthly) and on meteorological conditions, for example wind strength, wind direction and rainfall levels, which vary both daily and seasonally.

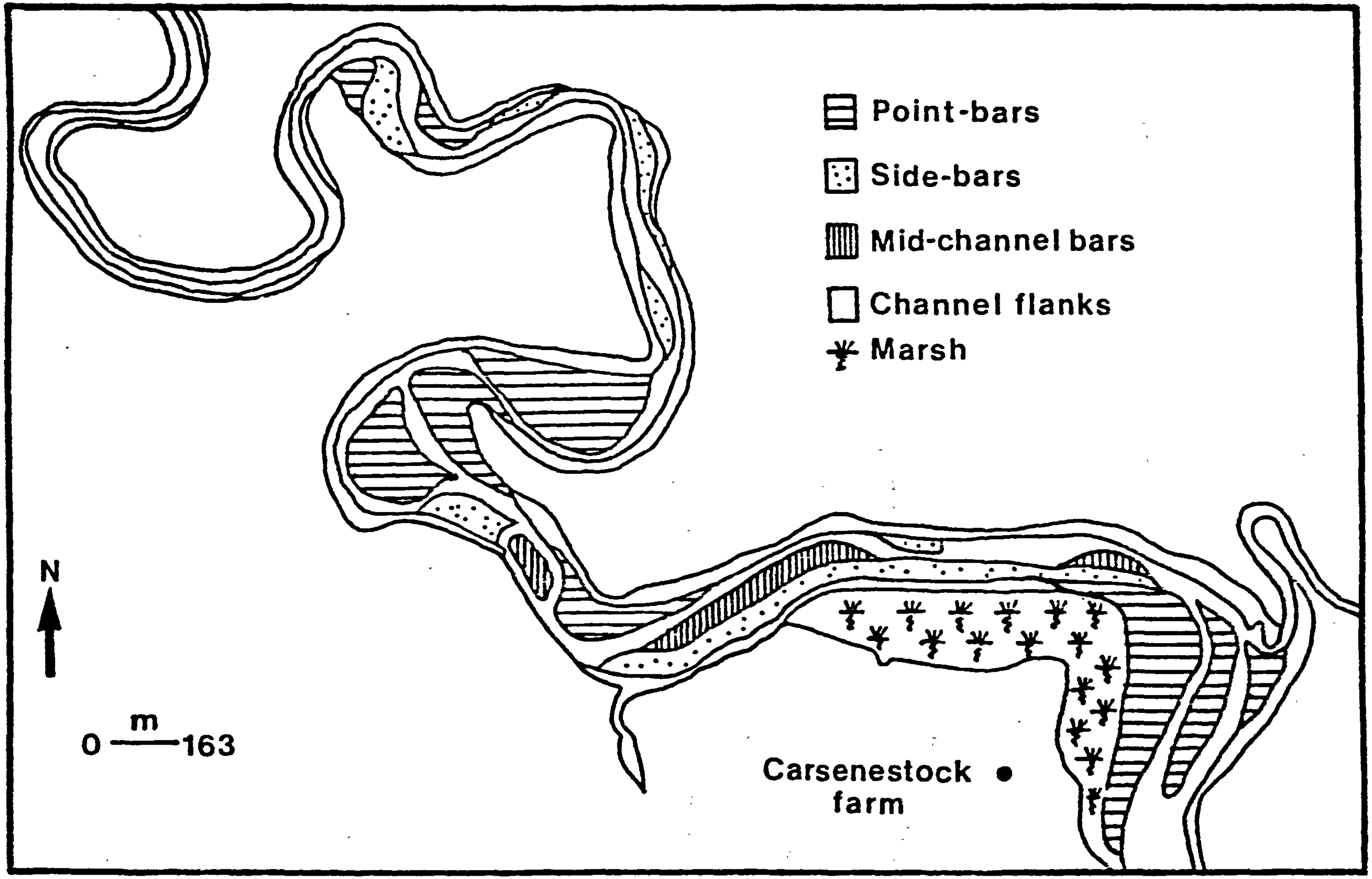


Fig.10.6 Distribution of low ebb stage bars, River Cree, in the vicinity of Carsenestock (traced from aerial photograph dated 1978, Scottish Development Department)

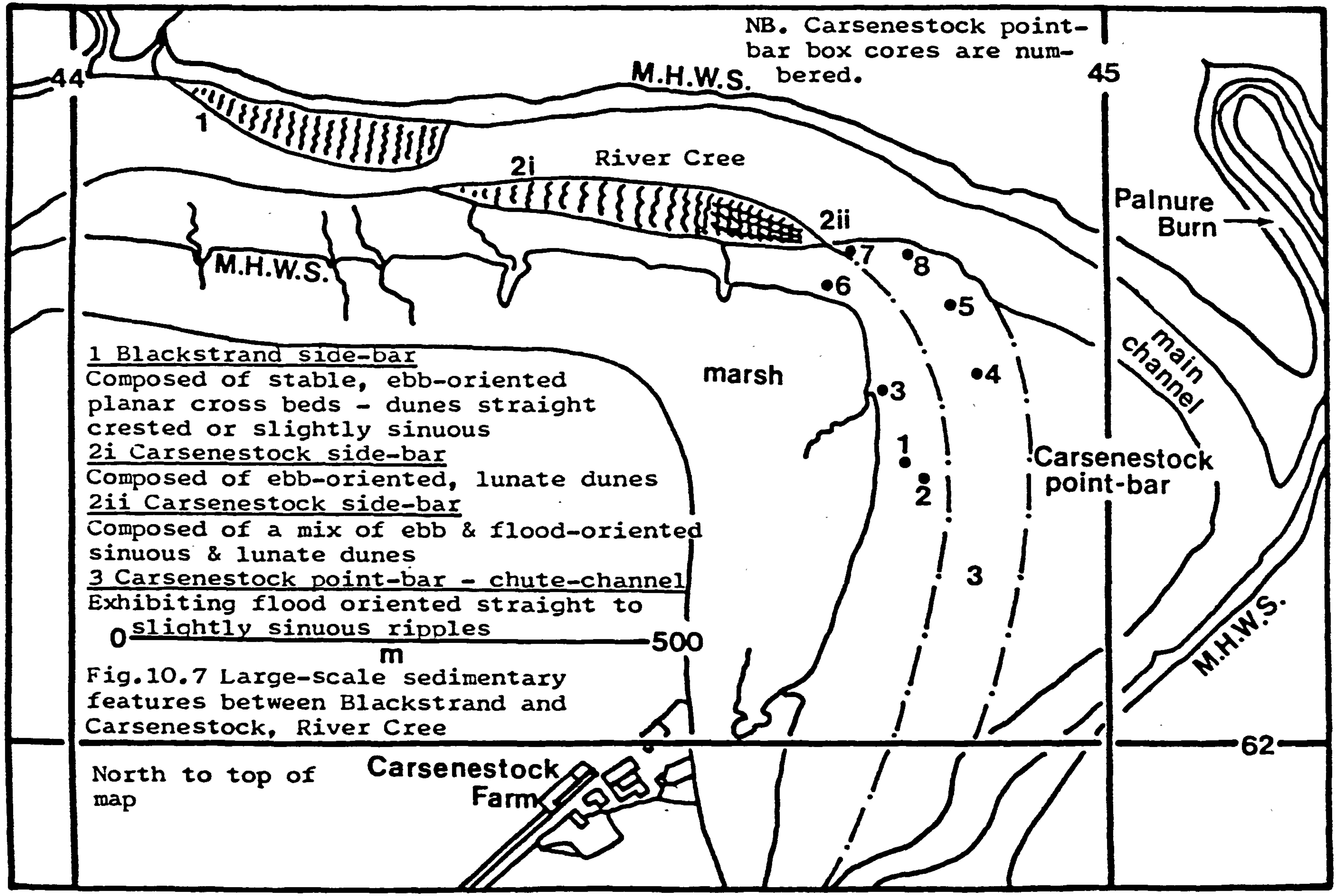


Fig.10.7 Large-scale sedimentary features between Blackstrand and Carsenestock, River Cree

These aforementioned variables affect the amount of water in the river system and the processes operating and, therefore, the structures formed at any given time.

The Carsenestock point-bar, for example, migrates during fairweather conditions, when fluvial discharge (confined to a single main channel) is reduced (i.e. in summer). The point-bar is destroyed under prolonged foul weather or storm conditions, which operate in late autumn, winter and very occasionally in summer when the River Cree is in spate. At these times flow is not confined to the main channel; water also occupies the upper chute-channel.

Since the box-core study was undertaken during fairweather conditions (i.e. in summer), it can be assumed that the preserved sedimentary features were constructed by dominant flood-tide processes under conditions of reduced river flow. Where ebb-flow features are preserved they indicate weak flood tides (therefore ebb-flow and/or fluvial dominance), an uncommon state during fairweather conditions.

If the above statement is true, then a predominance of ebb-flow features should be observable in winter, during high river discharges. This state was not proved, only hinted at during the very inclement weather in the summer of 1985 (see discussion, page 243).

10.2.3 Bar morphology

The following discussion of the study of the bars is based upon a period of casual observation and recording during a prolonged period of fairweather conditions in the summer of 1983. Further observation was undertaken during foulweather conditions in the summer of 1985.

Due to the restricted nature of observation and recording over short periods of time, it is obvious that the study will be biased towards the preservation of sedimentary features formed as a response to processes operating at a given point in time. Such a study would benefit from a longer-term monitoring of events.

10.2.3.1 Blackstrand side-bar - location NX 442 627

This bar has a triangular outline (Fig. 10.8a), pointing downstream, and is composed of stable ebb-oriented, straight-crested dunes that have a slight downstream migratory component. The bar remains stationary because, at the downstream tip (Fig. 10.8a), dunes are progressively destroyed by the main channel ebb flow. New feeder dunes form towards the rear of the bar near Blackstrand.

The dunes, constructed in coarse sand, are asymmetrical, with straight crest lines. Planar cross-sets dip (c. 20°) downstream. A typical section through a dune is shown in Fig. 10.8b. Stoss sides are littered with convex-up shells of Cerastoderma edule, whose umbones are flow-oriented in a downstream direction. There is a tendency towards concentration of shells at the front of the dune crests. An irregular basal lag of coarser-grade material (twigs, leaves, pebbles, dead oysters) is present below the cross-beds and in the troughs. Twigs are aligned at right angles to flow direction and have a tendency to be rolled along the channel-floor.

10.2.3.2 Carsenestock side-bar

Sedimentary features of the Carsenestock side-bar were recorded during the summer of 1983 under fairweather conditions. Destruction of the lower portion of this bar was recorded under foulweather conditions in the summer of 1985.

The Carsenestock side-bar is approximately 200 m in length and 50 m at its widest, merging with the flat channel floor of the River Cree (Fig. 10.9). The bar is divisible into two areas, A and B of Fig. 10.9. Area A is composed of

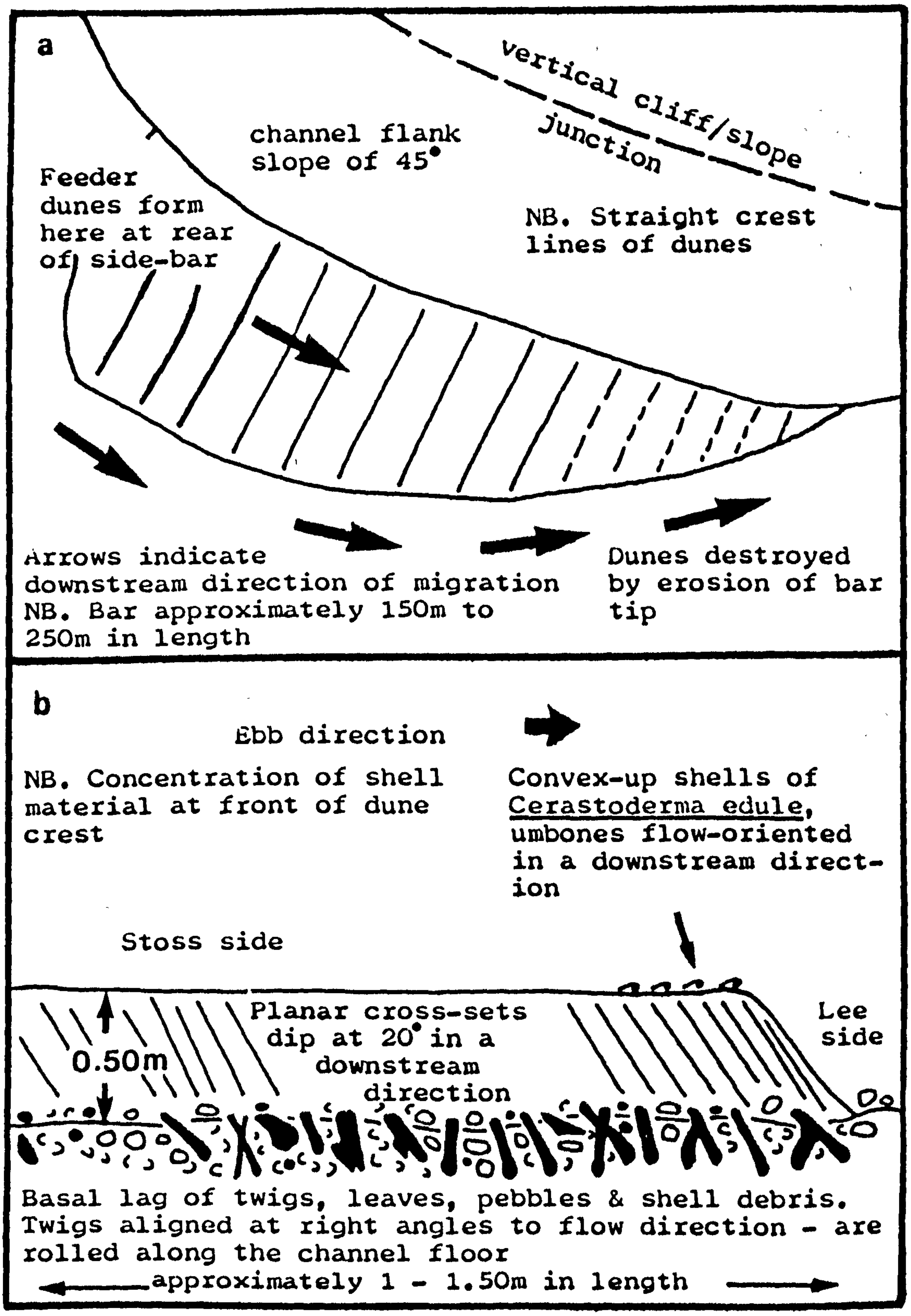


Fig.10.8a Plan view of the Blackstrand side-bar

Fig.10.8b Vertical section through a dune front, Blackstrand side-bar, River Cree

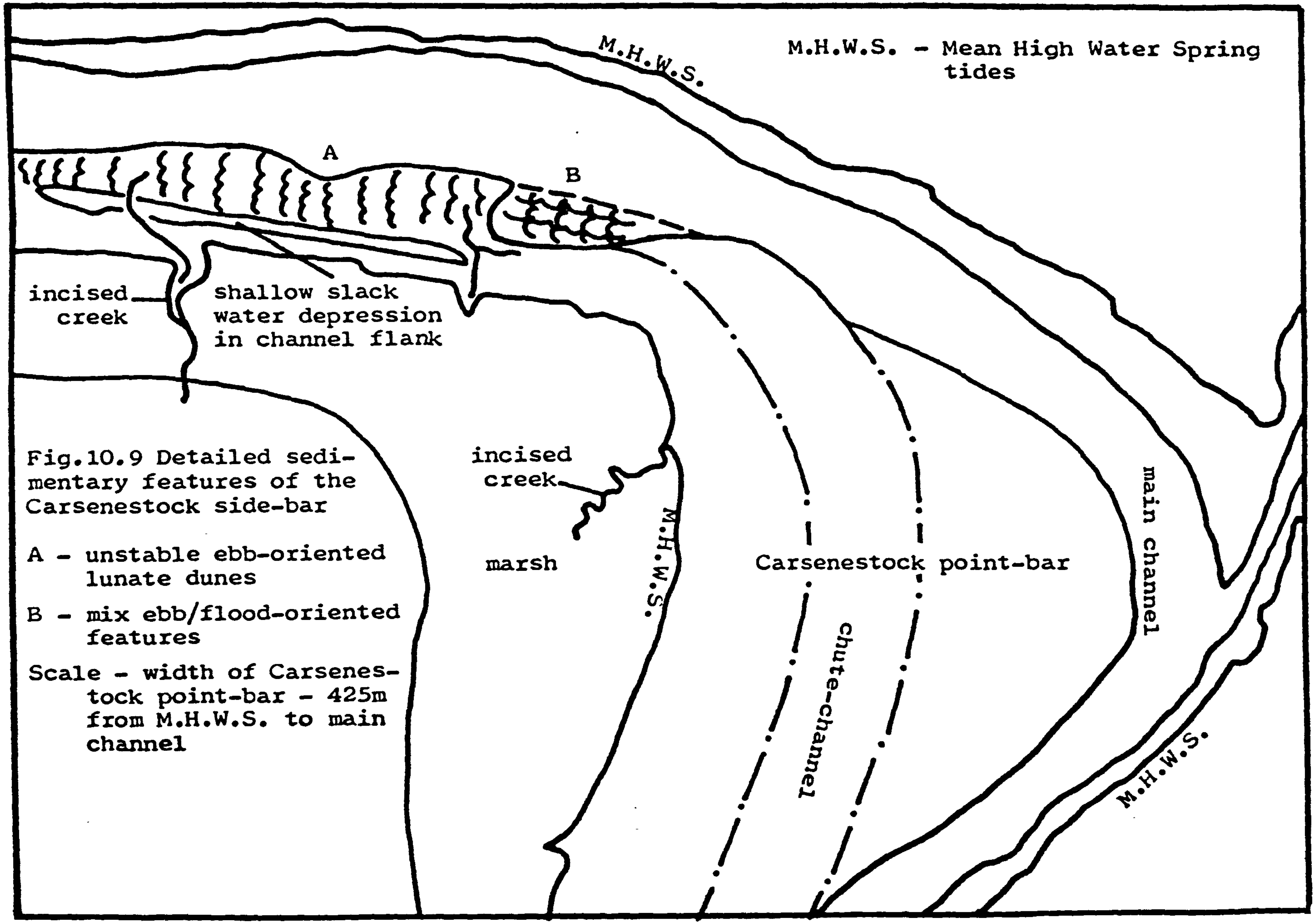


Fig.10.9 Detailed sedimentary features of the Carsenestock side-bar

A - unstable ebb-oriented lunate dunes

B - mix ebb/flood-oriented features

Scale - width of Carsenestock point-bar - 425m from M.H.W.S. to main channel unstable ebb-oriented lunate dunes which are destroyed by exceptionally strong flood tides or fluvial floods during the summer. New dunes always originate at the western tip of the bar and migrate downstream. Area B of the bar exhibits a complicated interference of ebb-and flood-oriented features, namely sinuous crested and lunate dunes, formed in coarse to very coarse sand. This interference pattern occurs as the Carsenestock side-bar merges with the Carsenestock point-bar and is influenced at this point by current flows as they move over the point-bar. The surface of the bar is undulatory as a result of this interference pattern. The dunes are frequently superimposed by smaller-scale sinuous crested wave ripples, formed as the current velocity wanes. Further modification of the bar surface into a two-level platform (Fig. 10.10a) occurs during late-stage draining of the ebb tide. Extensive semi-circular "rill-pans" are formed on the steep lee faces of the dunes and frequently coalesce with the adjacent pans (Fig. 10.10b). Individual rills are c. 0.03 to 0.05m in width and up to 0.10m in depth. They join to form a dendritic drainage pattern. Downcutting and erosion of the dunes is intense and rapid during the early stages of draining but slows down as the ebb tide recedes further. Water from higher-level rill-pans percolates downwards to the lower levels. The rill-pans are destroyed by the subsequent rising flood tide.

Under normal fairweather conditions the Carsenestock side-bar at B appears to be stable or undergoes lateral accretion where it merges with the Carsenestock point-bar (Fig. 10.11a).

However, after a period of foul weather conditions (heavy rains coupled with spring tides) during the summer of 1985, the Carsenestock side-bar at B and a part of the Carsenestock point-bar were destroyed as a result of a shift in river-channel position (Fig. 10.11b). A longitudinal bar formed on the outer (north) bank of the river, opposite the cut cliff, the outer bank becoming temporarily depositional in character. It is assumed that such foulweather conditions are more typical of an

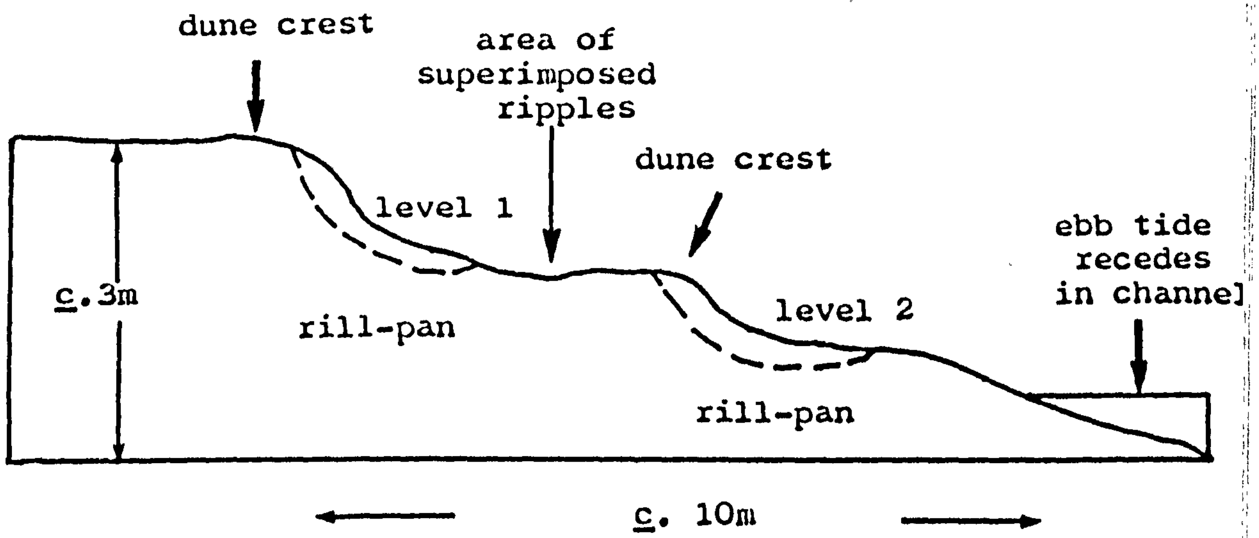


Fig.10.10a Section profile of the Carsenestock side-bar flank to show undulatory nature of bar surface

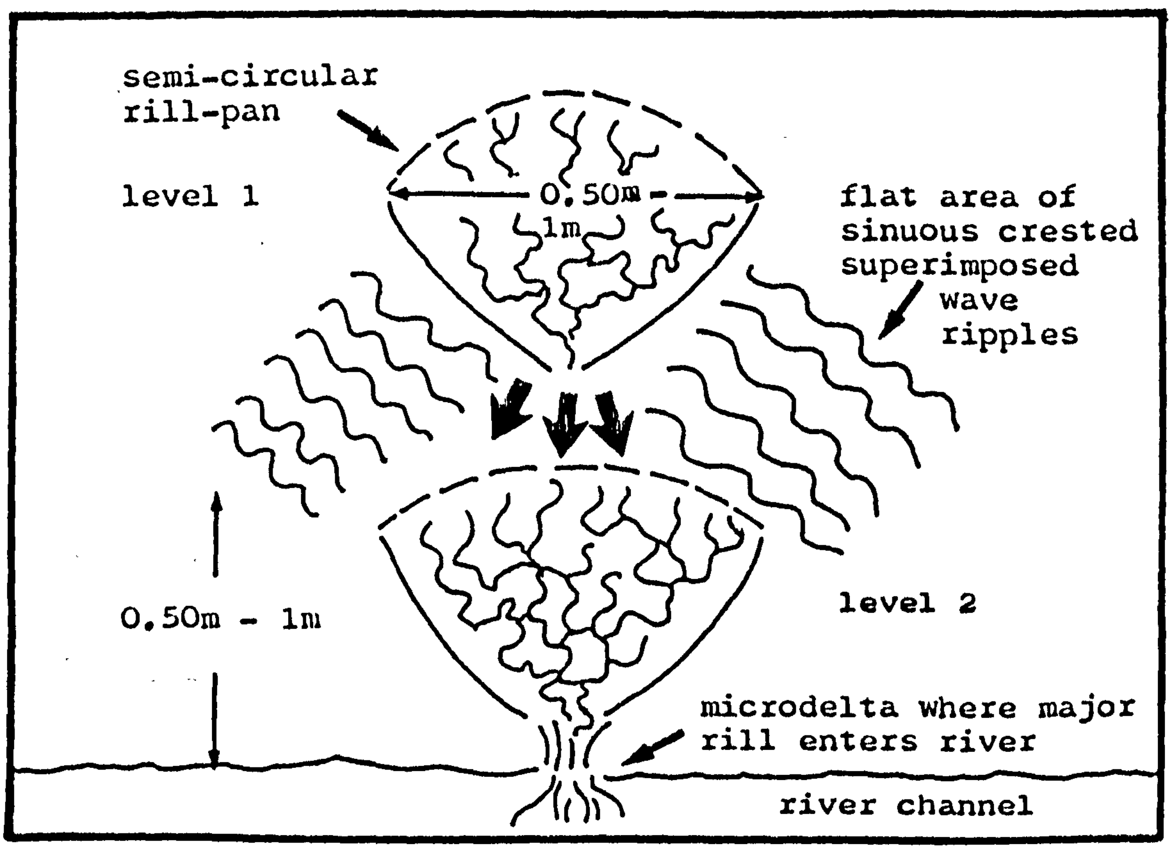


Fig.10.10b Plan view of the undulatory surface of the Carsenestock side-bar to show major late-stage drainage features. Thick arrows indicate direction of water seepage from level 1 to level 2

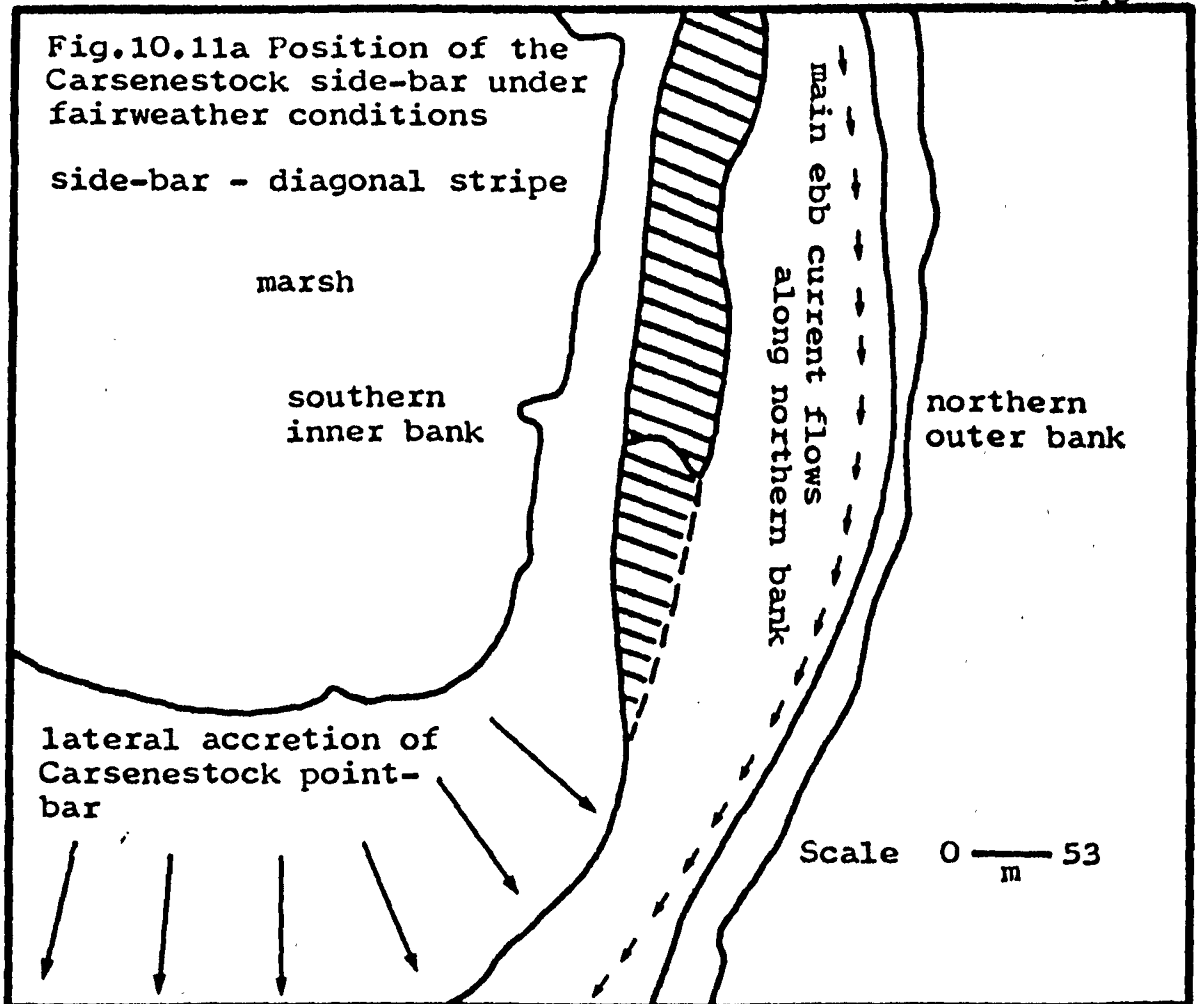


Fig.10.11a Position of the Carsenestock side-bar under fairweather conditions

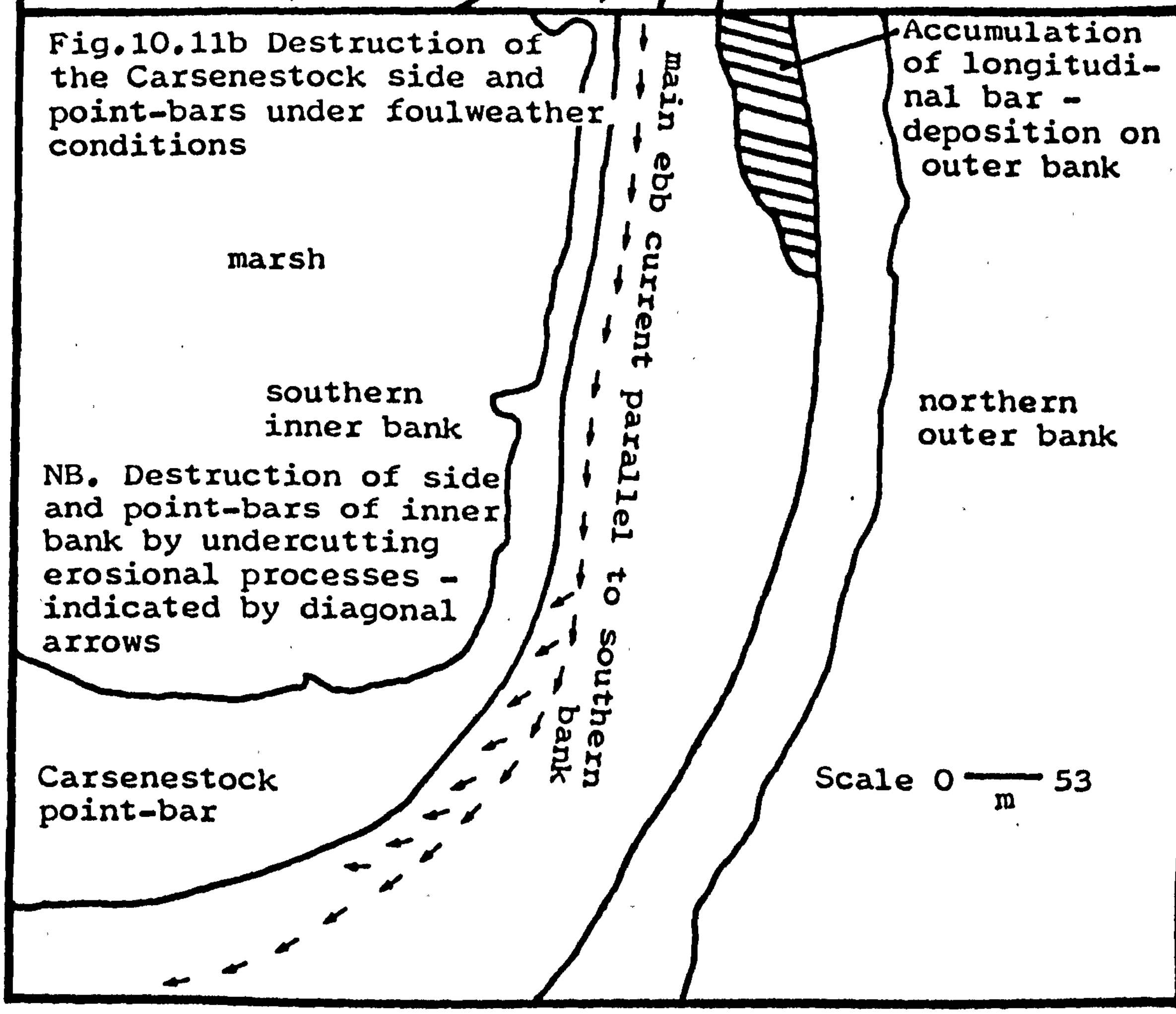


Fig.10.11b Destruction of the Carsenestock side and point-bars under foulweather conditions

autumn and winter situation, but the period of severe summer weather provided an insight into mechanisms of erosion that are chiefly confined to the winter.

The Carsenestock side-bar appeared to be completely destroyed and a vertical cliff was produced by undercutting processes at the channel-margin. The cliff extended for a distance of approximately 50m. Undercutting of the Carsenestock point-bar flank also occurred, in generally non-cohesive horizontally-bedded muds, silts and sand (Fig. 10.12). The 2 to 2.5m high cliff was formed under a rapidly-falling ebb tide, enhanced by fluvial flood discharge. As the ebb receded, vigorous under-cutting of the cliff occurred. The method of collapse was by toppling of large slices of the cliff face, or more frequently by small-scale rotational sliding of a projecting cliff face. Failure was aided by the sucking action produced by the falling ebb tide and the friction caused by wave action. The collapsed blocks once deposited on the channel-floor, were either "dissolved" completely to be carried away in suspension, or were modified by erosion and preserved by mud draping only when storm conditions abated. This would be particularly true of the larger blocks. Unfortunately, the channel floor was not exposed at low-water ebb stage and it was not possible to see if the blocks were present or not. Rates of erosion were considered to be extremely rapid - the cliff receded at a rate of c. 1 to 1.5m per hour - the rate of erosion decreasing with decreasing ebb-flow velocities and ceasing for a short period at low water. However, as the flood tide progressed upstream, erosion was re-commenced, with rates increasing as flood-tide current velocities increased. Generally, erosion rates were lower on a flood tide than on an ebb, due to the fact that the flood-tide current velocities were slowed and weakened by the exceptionally high and opposing fluvial discharge.

Due to the temporary shift in river-channel position, the inner bank became erosional whilst, opposite the previously described cliff, a longitudinal river-channel side-bar was

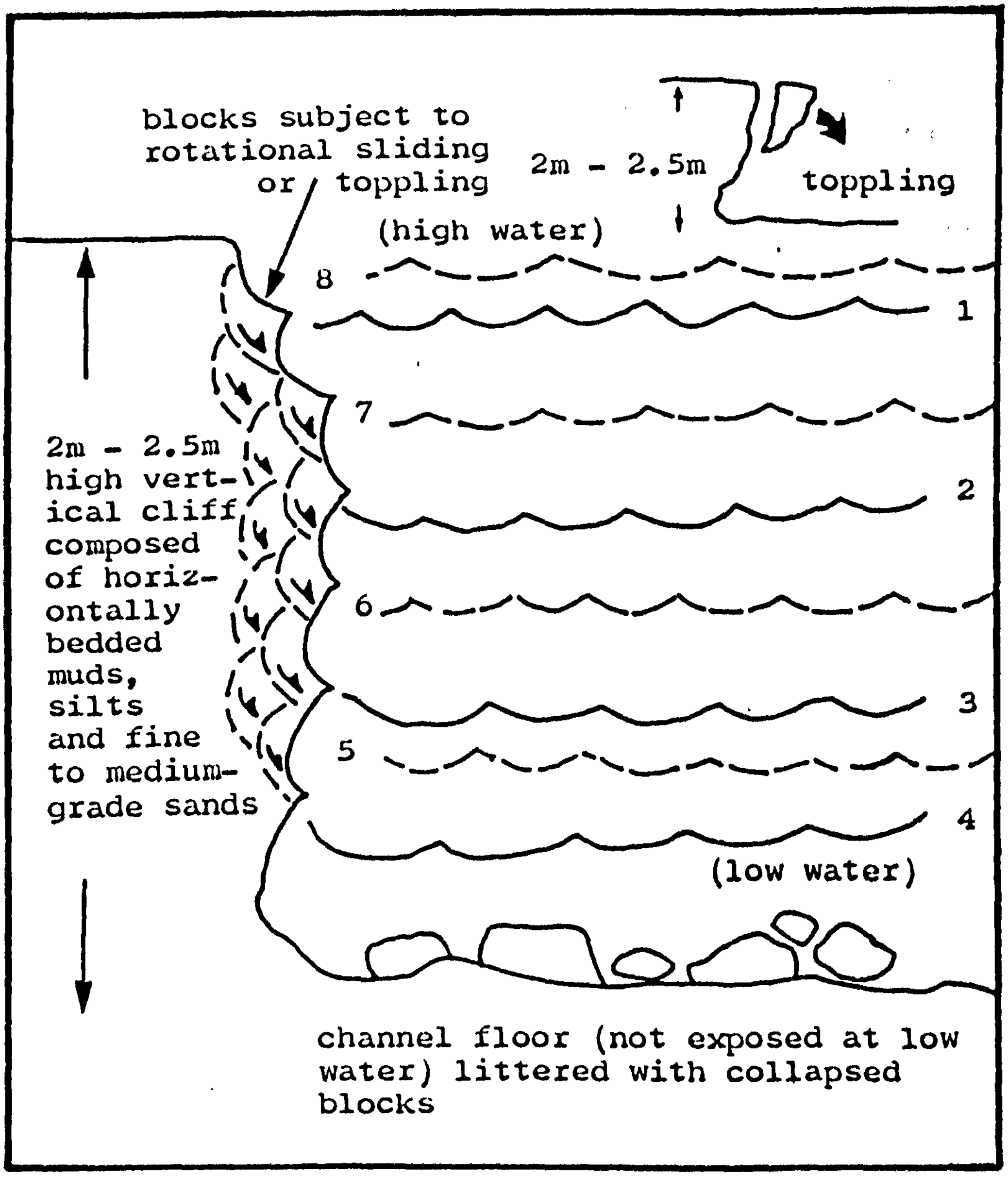


Fig.10.12 Profile of the cliff at Carsenestock, River Cree which exhibits undercutting and erosion. 1 - 2 - 3 - 4 Successive positions of the level of the receding ebb tide. 5 - 6 - 7 - 8 Successive positions of the level of the rising flood tide. Outer layer of slide blocks collapses as the ebb tide falls, inner layer of slide blocks collapses as the flood tide rises

formed, the outer bank now being subject to deposition.

The side-bar, approximately 200 m in length and 50 m in width (Fig. 10.13), was composed of ebb-oriented sinuous crested dunes c. 0.50m in height, with wavelengths of 1 to 1.50m, constructed in compact coarse sand. Pools of water were common on the surface. The lee faces of the dunes were frequently draped by medium-grade sand, forming superimposed ripples.

The side-bar remained stable for four days after storm conditions had abated. After this period, when fluvial conditions returned to normal, discharge patterns and flood tides increased in strength relative to fluvial and ebb outflow, the bar was gradually destroyed (Fig. 10.13, inset). The side-bar front was eroded by the flood tide, only to be reworked and fashioned into a curved spit by the subsequent ebb tide.

10.2.3.3 Carsenestock point-bar

The Carsenestock point-bar (Fig. 10.14) is a product of large-scale lateral accretion in the wake of eastward and north-eastward migration of the River Cree. The point-bar extends approximately 425m at its widest point, measured W to E from the marsh edge/point-bar contact to the main-channel margin at low water. It is composed chiefly of fine-grained sediments (sands, silts and clays) and this factor combined with the broadness of the meander results in a gentle profile (Fig. 10.15), with beds dipping at very low angles into the main channel. The point-bar is traversed (in a N to S direction) by a chute-channel (Figs. 10.14 and 10.15), which contains coarse sand and channel-lag debris in contrast with the surrounding finer-grade deposits. The chute-channel is a shallow depression, approximately 100m wide. It divides the point-bar into upper and lower sections. Its function is that of an overspill channel for the main channel of the River Cree as the flood and ebb tides rise and fall and pass upstream and downstream respectively.

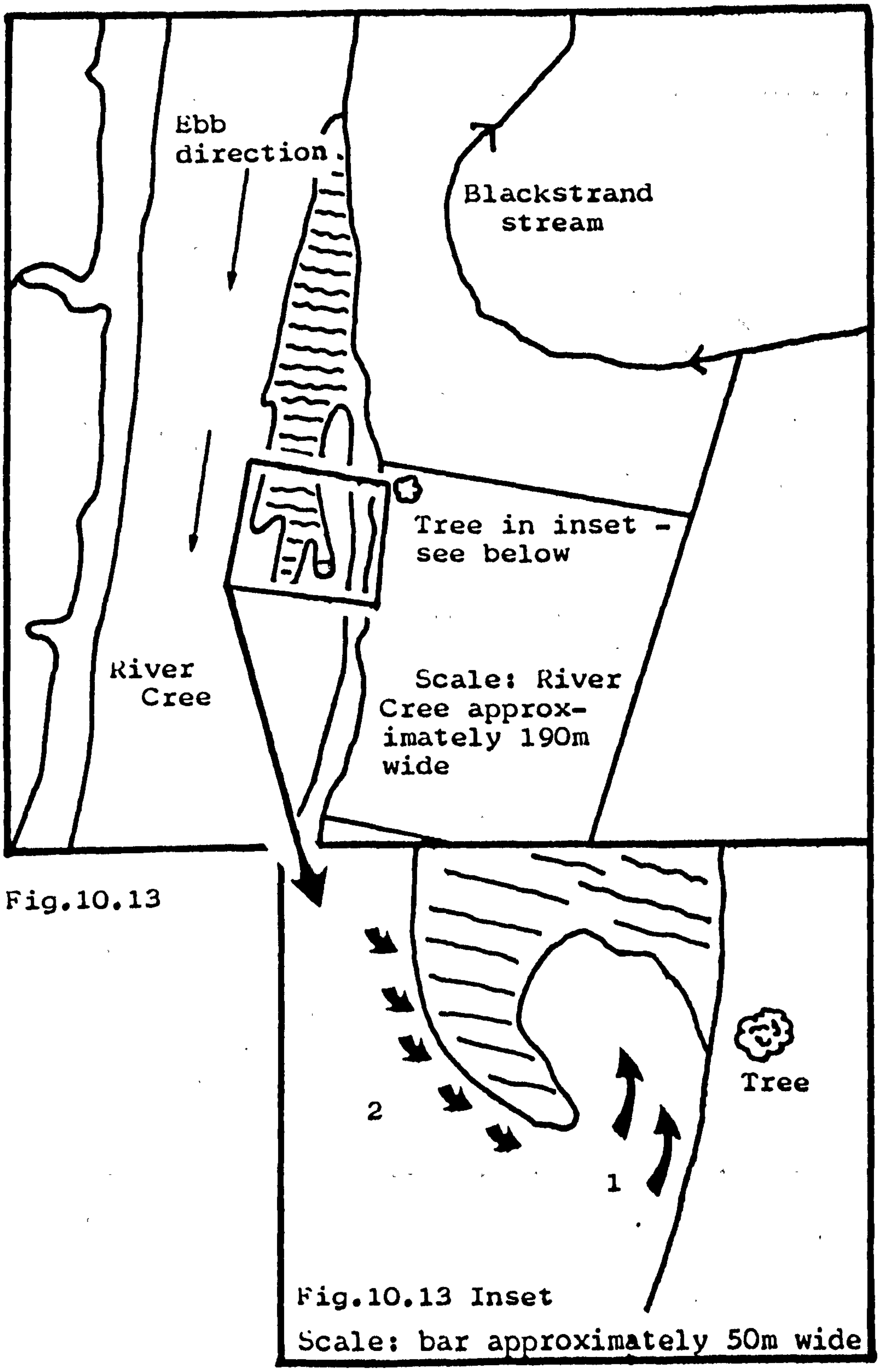


Fig.10.13 "Temporary" side-bar opposite vertical cliff at Carsenestock - 20.7.85. Inset: Destruction of temporary side-bar - 24.7.85. 1 Erosion of bar front by flood tide. 2 Re-shaping of bar front into spit by ebb tide. NB. North to the right of the map.

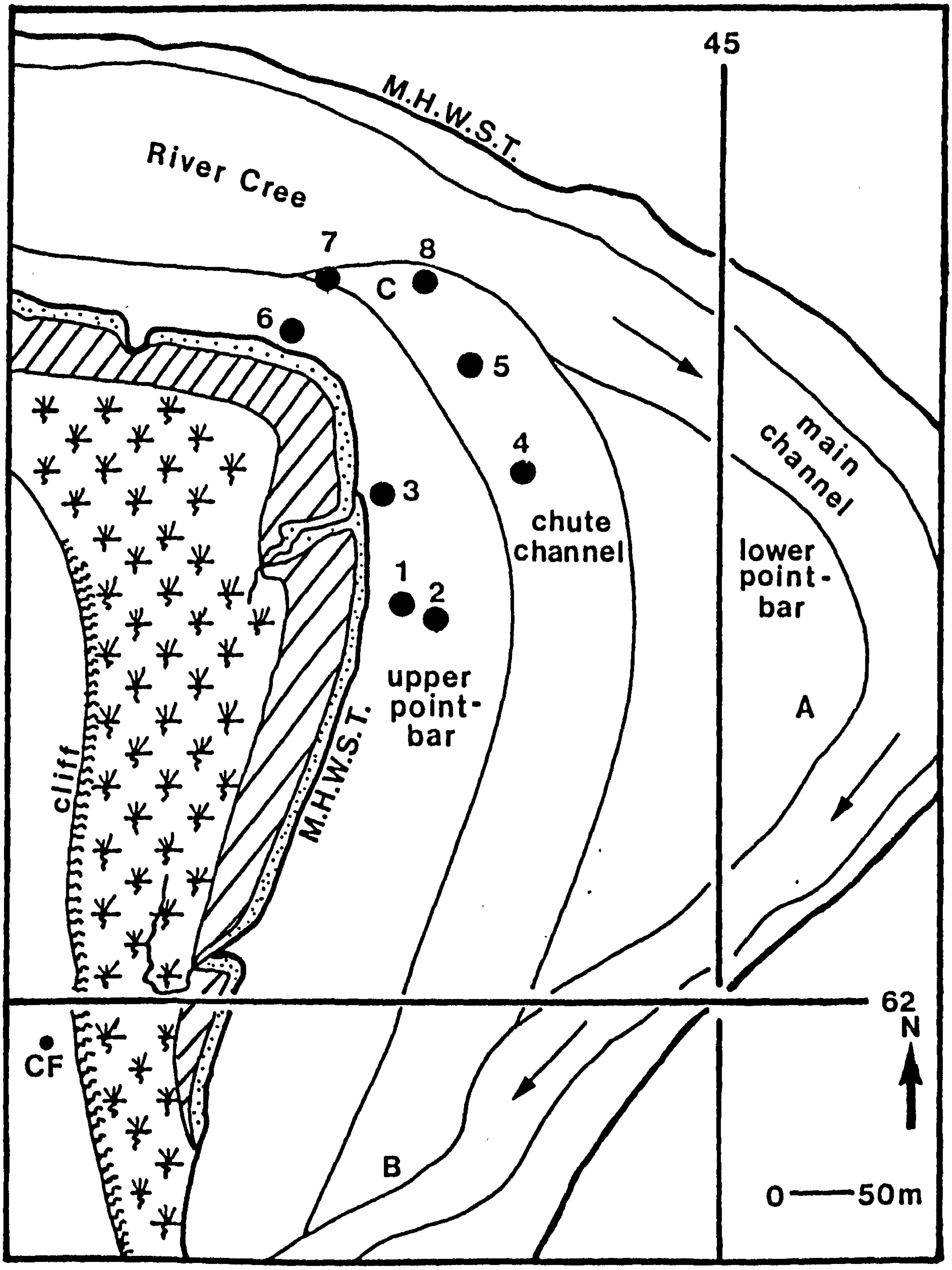


Fig.10.14 Physiography of the Carsenestock point-bar together with box-core positions (numbered).
CF - Carsenestock farm, A - lower point-bar, B and C - chute-channel/main channel contacts. Arrows in main channel indicate ebb direction. Marsh ornamentation - salt-tolerant marsh, dotted, marsh subject to flooding by spring tides/storm surges, diagonal stripe, supratidal marsh, marsh symbol. Cliff margin is hachured

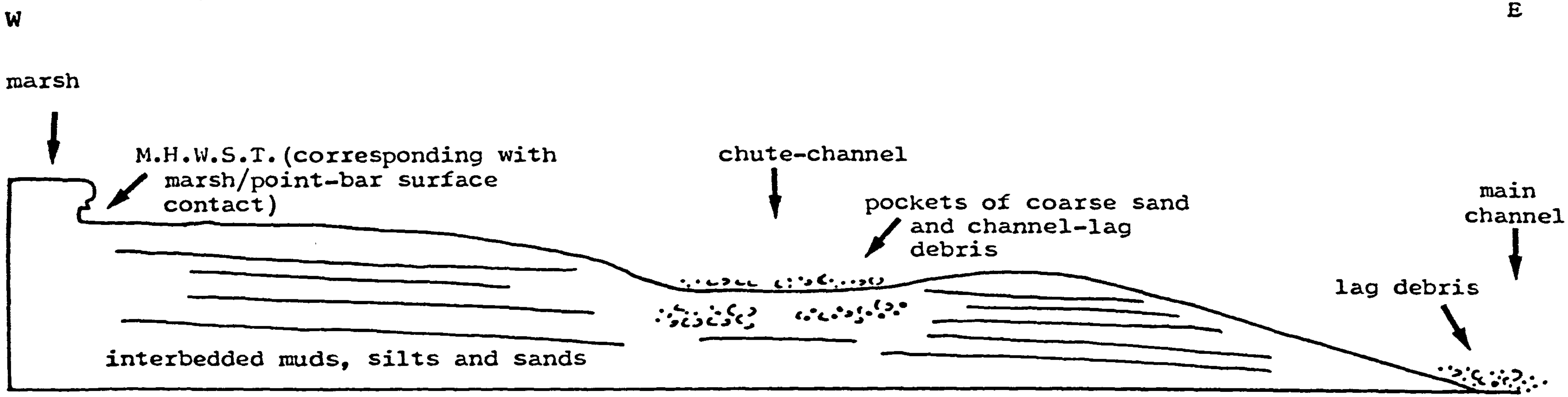


Fig.10.15 West to east profile across the Carsenestock point-bar. Distance W to E - 425m . Point-bar sediments c. 3 to 4m in thickness

When the flood tide approached the Carsenestock meander most of the flow was confined to the main channel. The flow would gradually cover the lower point-bar at A (see Fig. 10.14) near the confluence of the Palnure Burn with the main channel of the River Cree. Simultaneously, water would enter the lower end of the chute-channel at B and proceed rapidly to C, by-passing the lower point-bar and leaving it exposed. With time, however, the lower point-bar, chute-channel and upper point-bar are covered by the rising tide.

As the ebb drains, the chute-channel is exposed first, followed by the lower point-bar, as the ebb falls in the main channel. Depending upon the amount of fluvial discharge in addition to the ebb flow, the chute-channel either may be abandoned of its flow early in the ebb phase (i.e. if ebb tides are low and there is little fluvial discharge) or late in the ebb phase if discharge/tides rates are higher. The box-core study was undertaken under low fluvial discharge and ebb conditions. It was noted that shallow pools of water collected and remained in the chute-channel throughout the ebb phase and at slack water, as a result of late-stage draining of the upper point-bar.

The upper point-bar at Carsenestock is backed by fine-grained merse deposits which form a marsh (Figs. 10.14 and 10.15). The marsh/point-bar contact is marked by a cliff c. 0.30 to 0.50m in height and is erosional along the whole length of the inner margin of the upper point-bar at M.H.W.S.T. Several deeply-incised meandering creeks drain the marsh. The marsh is divided into three zones which are flooded, with varying frequency, by high tides. The Carsenestock point-bar is covered at high tide by all tides, although occasionally the upper 2m of the upper point-bar may remain uncovered at very low neap tides. The marsh zones immediately adjacent to the upper point-bar, c. 5 to 10m wide (Fig. 10.14, dotted), are composed of short, stunted salt-tolerant vegetation as a result of frequent inundation of the marsh edge by high spring tides. A strand line of debris, lying parallel to the marsh margin and marking the level of highest water, is frequently present on the marsh surface. Landward of this salt-tolerant zone, lies a broader belt of marsh, up to 50m in width (Fig. 10.14,diagonal stripe), subject to occasional flooding by high spring tides and storm surging. A third zone, of grassy marsh, up to 200m in width, extends westwards to a small cliff (Fig. 10.14,hachured). It is completely supratidal, except under extreme storm-surge conditions, when extensive flooding may occur. Under these conditions, pools of sea and rainwater remain on the marsh surface for several days after the storm has abated. The water is readily retained due to the impervious nature of the underlying clayey deposits.

<u>Box-core positions</u>

Box-cores (1,2,3 & 6) were sited in fine-grained deposits of the upper point-bar and coarser-grade chute-channel deposits (boxes 4 & 5), to record the salient characteristics and sedimentary features and to gain an insight into the processes operating at these locations. Box 7 was located in the main channel of the River Cree at the northern end of the chute-channel. Although the lower point-bar was exposed during the box-coring exercise, no samples were taken, as the deposits remained water saturated and non-cohesive.

An account of the sedimentary structures as exhibited in the box-cores collected at Carsenestock is now given.

10.2.4 Sedimentary structures of the Carsenestock point-bar as exhibited in the box-cores

Sedimentary features, characteristic of both upper point-bar and channel environments, were recorded in box-cores (Fig. 10.16) and preserved as peels. The features are described in detail below, from a high to low location on the point-bar. Conclusions reached on the basis of the detailed descriptions are given later in this chapter, page 271.

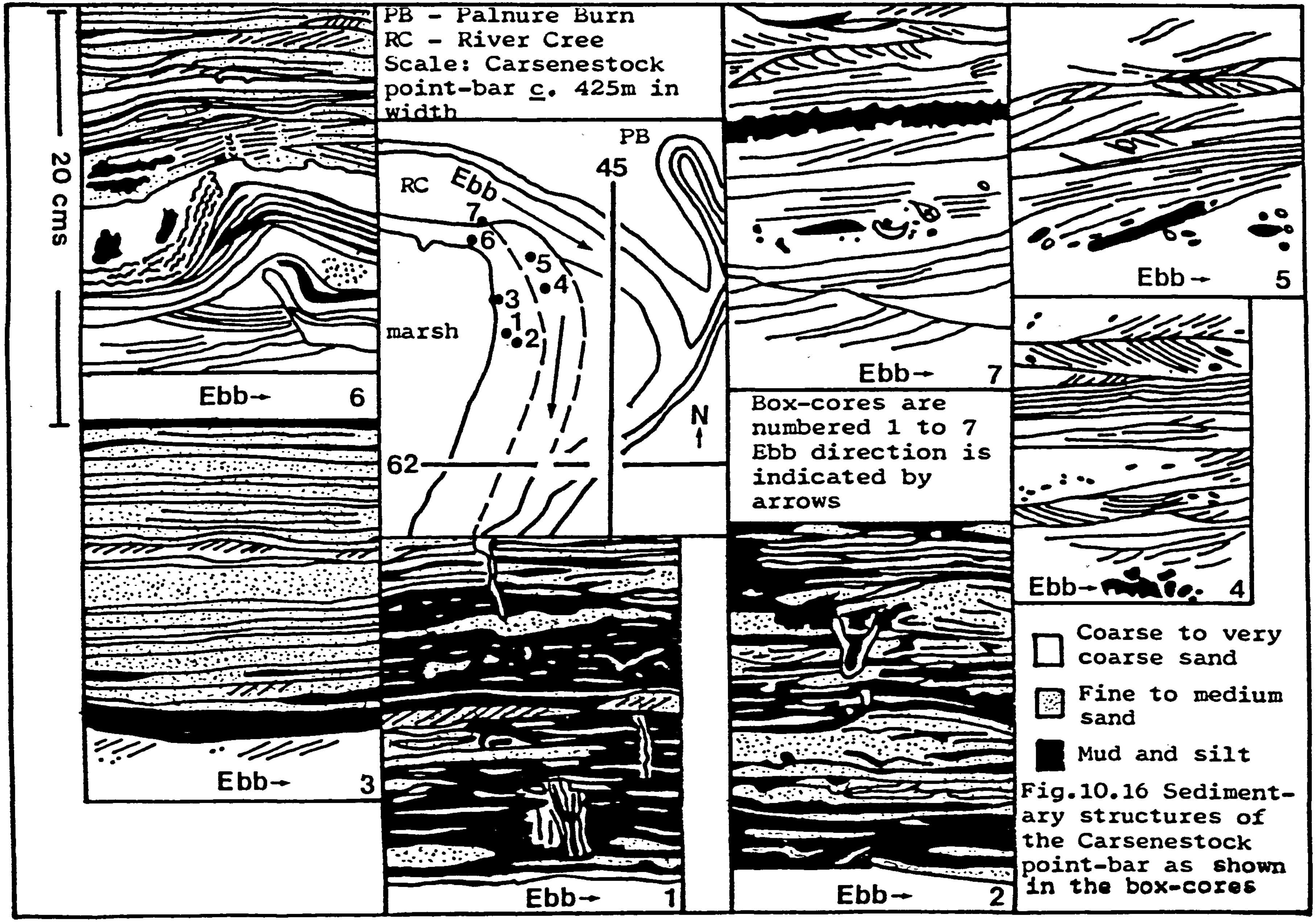


Fig.10.16 Sedimentary structures of the Carsenestock point-bar as shown in the box-cores

Box-core Peel 3 - upper point-bar

Box-core peel 3 was sited on the flank of a bank of a small, but deeply incised, creek where it met the point-bar (Fig. 10.17). The sediment preserved in the box-core and peel consists of fining- and thinning-upwards alternate layers of medium- to fine-sand and mud. Overall sand content is c. 95%. Apart from a c. 0.02m thick mud lamina at the base of the box-core, mud laminae have a constant thickness of c. 2 - 4mm. They are most frequent in the topmost 0.08m of the core. Coarse sand is present at the base forming small-scale (c. 0.03m high) flood-oriented ripples. Cross-sets are planar, and a few millimetres in thickness. Deposition of these sediments was followed by a quiet period of deposition of fine-grained mud and silt from suspension at slack water, the sediment infilling troughs between the ripples and eventually blanketing them. Fine vegetational wisps are present within the silts. Above the thick mud layer are seven medium-grade sand and mud couplets. Sand units are c. 1.5cm in thickness and display unidirectional (flood-oriented) planar cross-sets c. 0.5 to 1mm thick and dipping at 8^{o}. The cross-sets are marked by inclined lines of faecal pellet holes, the pellets having been eroded or washed out. The small-scale ripples formed under a weak and waning current towards the close of high-water conditions. They are horizontally truncated and overlain by a thin layer of mud that was deposited from suspension at slack water. The mud layer is immediately overlain by the next sand unit of the succeeding flood tide. No intervening ebb-oriented features were noted. A few poorly-developed mud flasers are evident in the topmost couplet. The top 0.08m of the core is predominantly muddy. Alternations are horizontal.

Box-core Peel 6 - upper point bar

Box-core peel 6, located on the upper point-bar close to the cliff at the edge of the marsh, exhibits small-scale post-depositional deformation in compact sediment, together with brittle and plastic failure, possibly triggered by collapse of

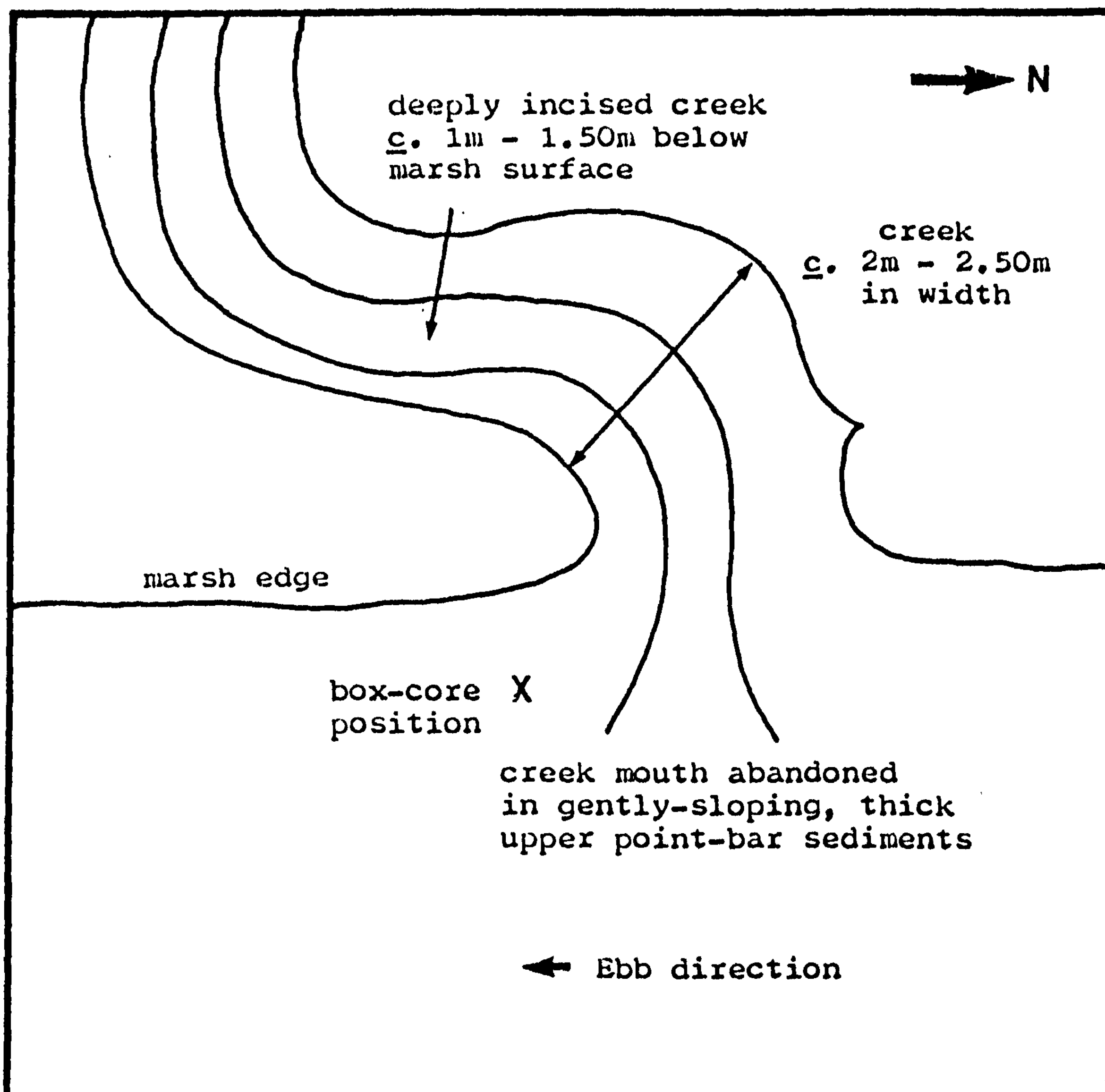


Fig.10.17 Map to show position of box-core 3, Carsenestock point-bar, River Cree

the nearby marsh edge. In the lower half of the box-core, medium-grade sand and mud alternations (similar to those of box-core 3) are folded. The core of the fold is in a thick (c. 0.02m) layer of medium-grade sand which has undergone brittle fracturing. The thinner alternations overlying the core, and composed of mud and medium-grade sand, have behaved plastically and have been folded. The fold is in turn overlain by a disturbed zone, where less-cohesive medium-grade sand is thrown into a chaotic slump. Water-escape features are evident immediately above this zone, indicating that the sediment that was subjected to the sudden shock was waterlogged.

The upper 0.06m of the box-core exhibits good examples of small-scale flood-oriented ripples alternating with muds and silts deposited from suspension, similar to those of box-core 3.

Flood-oriented ripples exhibit re-activation surfaces as a result of either falling-stage modification of the bedform or sub-ordinate flood tidal flow followed by a further period of dominant flow. Stoss-side preservation is evident as also is reworking of stoss-side sediment into the preceding trough (to form counter-current ripple cross stratification) by a counter-current. This may result from separated flow in the lee of the preceding bedform or counter-current ripple stratification may be the result of sub-ordinate ebb flow. Climbing ripples are also present. All these features indicate active migration, deposition and reworking despite a very weak flood-current flow. Finely-crushed leaf fragments were frequently incorporated into the mud units, often occupying ripple troughs. It is interesting to note that post-depositional deformation and ejection of water from these loosely-consolidated deposits has been triggered by the movement of animals (herd of cows) over the upper point-bar.

<u>Box-core Peel 1</u> - mid upper point-bar

Box-core peel 1 was sited <u>c</u>. 5m east of the marsh edge and lower on the point-bar than the previously described cores. The adjacent point-bar surface was prone to dessication; a patchy, discontinuous layer of loose, fine dry sand was present, together with curled mud flakes in muddier areas. Where the point-bar surface was moister, imprints of birds' feet and holes formed as a result of pecking were recorded. Scattered debris, such as twigs and dried seaweed, was common. No strandline was discernible, suggesting that tidal action at the time of recording was relatively weak.

Fine to medium-grade sand and mud are present in equal proportions in box-core peel 1. The basal 0.05m of the core exhibits alternating lenses of mud and fine sand (or discontinuous laminae) the latter between 2mm and 0.01m in thickness. The layers are inclined gently (<u>c</u>. 1^{o} - 2^{o}) in a flood-tide direction. The mud or silt interval is very micaceous. Rare examples of groups of straight, 1 - 2mm wide, burrows were preserved. Although the alternations indicate rapidly fluctuating energy conditions, the environment was stable a sufficient length of time to allow burrowing by organisms, possibly during a prolonged period of fairweather conditions and/or a gentle phase of the monthly tidal cycle. Sand lenses increase in proportion within the overlying 0.05m, becoming continuous layers and slightly coarser in grade (<u>i.e.</u> medium to coarse sand). Traces of flood-oriented planar cross-laminations (inclined at <u>c</u>. 5^{o}) are preserved in poorly-developed ripples. They are abruptly truncated by the succeeding mud interval. The aforementioned couplets are less well developed than those in box-core 3.

Upwards, a 0.01m thick sand layer follows, fashioned into a small-scale flood-oriented ripple (Fig. 10.18). Planar cross-laminations are marked by lines of holes left by the washout of faecal pellets. The ripple is truncated by mud deposited from suspension.

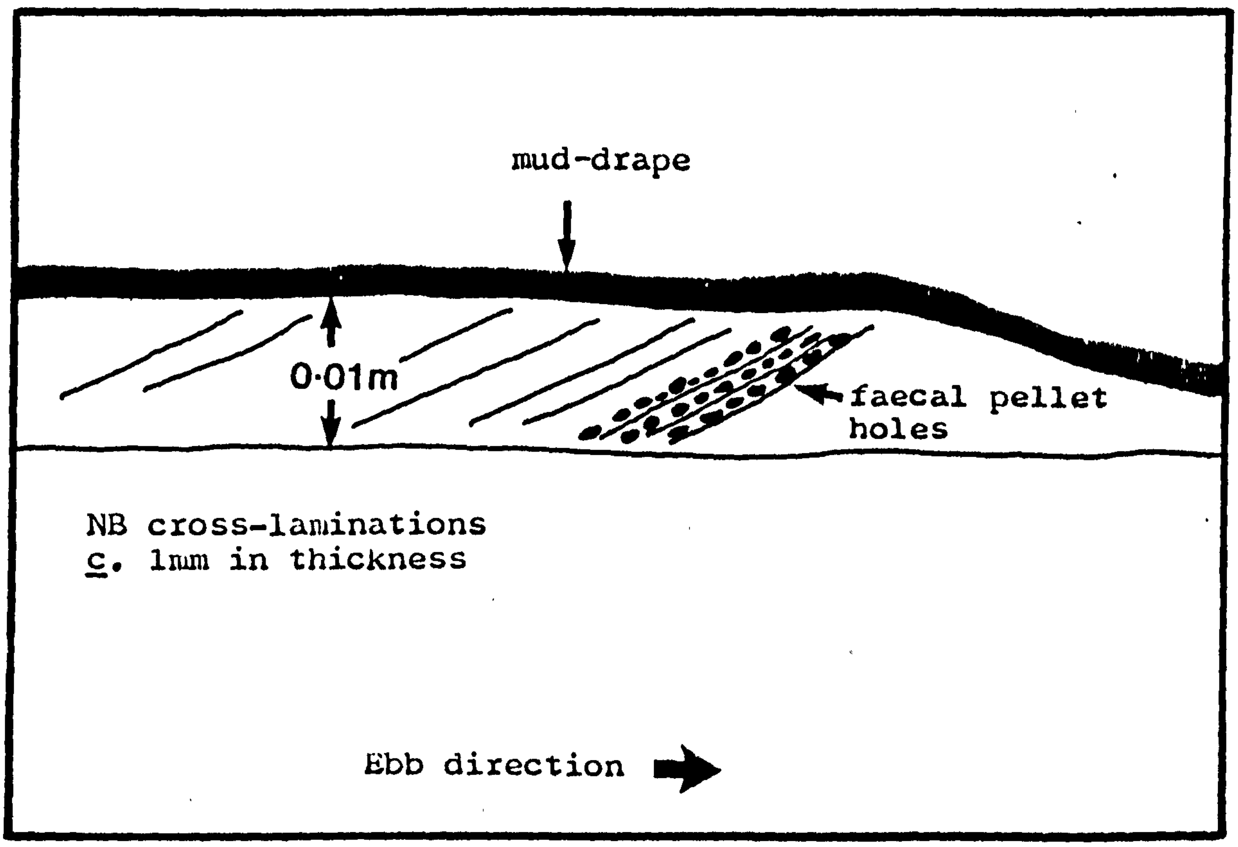


Fig.10.18 Flood-oriented ripple in coarse sand, box-core peel 1, Carsenestock point-bar. NB Width of sketch c. 0.10m

A disturbed zone, 0.04m in thickness, overlies the sand. Alternating mud and sand layers are broken and churned up. Sand layers display a downward deflection of their disrupted margins. The disturbance is probably due to bioturbation and reworking of the sediment by burrowing organisms. Such activity would be enhanced by stable fairweather, under conditions of lower environmental energy. A thin (0.5cm) layer of fine sand, immediately above the disturbed zone, is riddled with abundant holes from which faecal pellets have been eroded. This provides additional evidence for the presence of burrowing animals within the underlying bioturbated zone.

The topmost 0.03m of box-core sediment consists of poorly-developed sand and mud couplets. Sand layers are c. 2 - 3mm in thickness. Small-scale flood-oriented ripples, exhibiting re-activation surfaces, are present.

Box-core Peel 2 - mid upper point-bar

Three distinct phases of change in environmental energy are evident within box-core peel 2. The lowest 0.09m of the box-core sediment consists of alternating medium-grade to slightly coarse-grade sand and mud couplets. Faint traces of flood-oriented ripple cross-laminations are evident within a few of the sand units. Environmental energy was fluctuating rapidly and was relatively high.

Upwards, there follows c. 0.06m of thinner alternating sand and mud couplets that were deposited under relatively lower-energy conditions. Both the sand and the mud units average 2 - 3mm in thickness. The quieter phase of deposition has allowed habitation by infauna. A well-preserved U-shaped burrow is present (Fig. 10.19). The unknown occupant of the burrow escaped in response to a sudden change in energy conditions, which produced the sand ripple that now overlies the burrow. The animal moved upwards, infilling its burrow as it went. Surprisingly, this action has not caused the

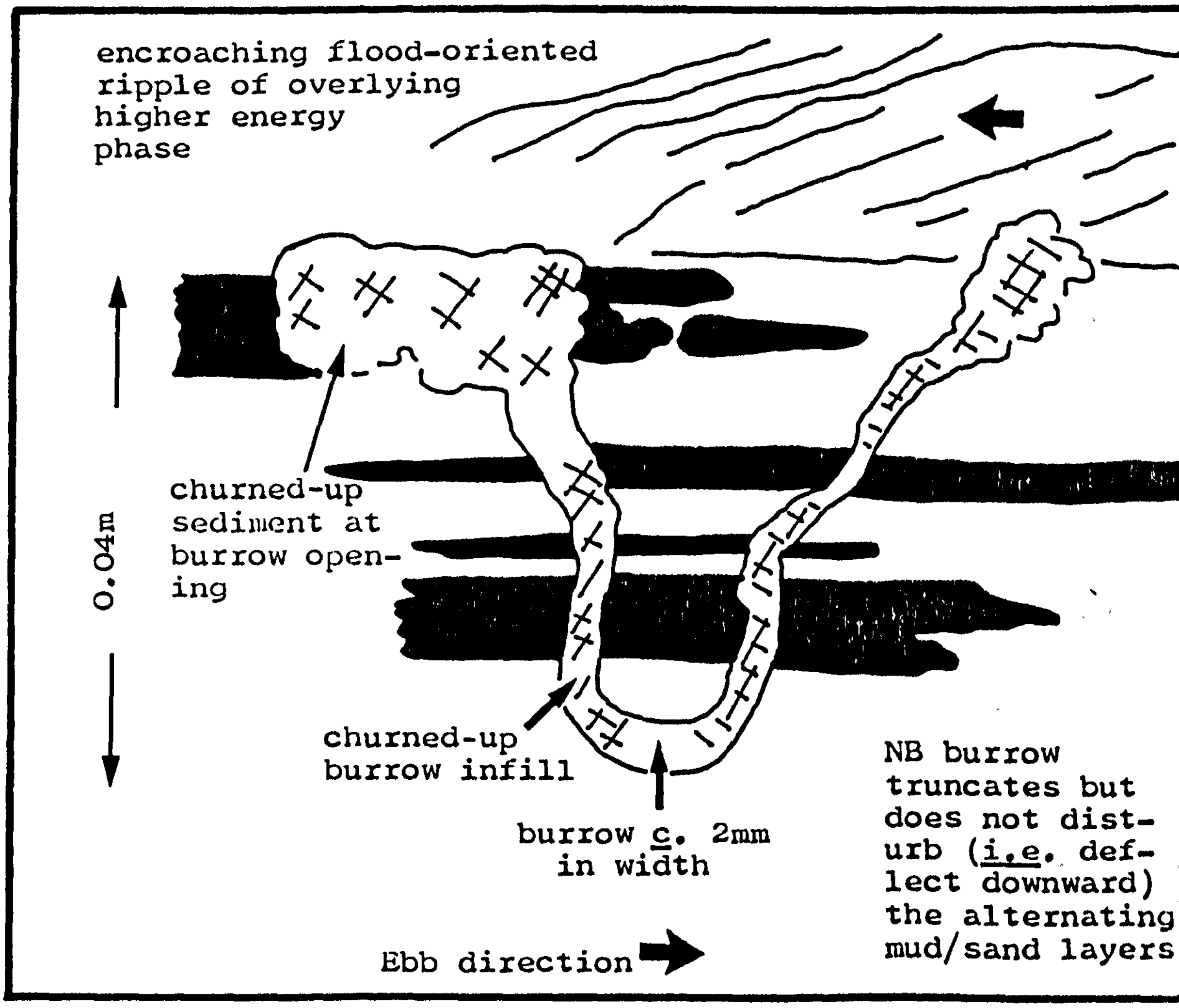


Fig.10.19 U-shaped burrow, box-core peel 2, Carsenestock point-bar

typical downward deflection of truncated sediment layers at the margins of the burrow. This may be due to the fact that upward movement was slow, causing minimal disturbance of the surrounding layers, combined with the relatively compact nature of the sediments, which allowed sharp, brittle truncation of the layers rather than plastic downward folding, which occurs when sediment is loosely consolidated and waterlogged.

Energy was again relatively high during deposition of the topmost 0.07m of sediment in the box-core above the burrow. A flood-oriented ripple that migrated over the burrow is well-preserved. Several re-activation surfaces are present on its lee face (Fig. 10.20), illustrating the "stop-and-start" nature of ripple migration as a result of fluctuations in unidirectional current flow. During a subsequent period of higher energy, when erosion was dominant and no further ripples were being formed, the top of the flood-oriented ripple was levelled and draped by a horizontal layer of mud c. 2mm in thickness. Energy levels remain constantly fluctuating but generally high to the top of the box-core.

Box-core Peels 4, 5 and 7 - chute-channel, mid point-bar

Sediment textures and structures recorded in box-cores 4, 5 and 7, located in the chute-channel, record typical channel processes, similar to those operating in the main channel of the River Cree, but on a smaller-scale as the chute-channel is shallower and its deposits are thinner.

Box-core Peel 4 - chute-channel, mid point-bar

The above box-core (Fig. 10.21) exhibits well-preserved examples of reversed and unidirectional ripple forms giving rise to bi-directional herringbone cross-stratification that overlies typical channel-floor lag debris. Erosion surfaces are frequent.

A basal lag of leaf and clay/mud pebble debris is present at the base of the box-core, indicating the presence of channel-

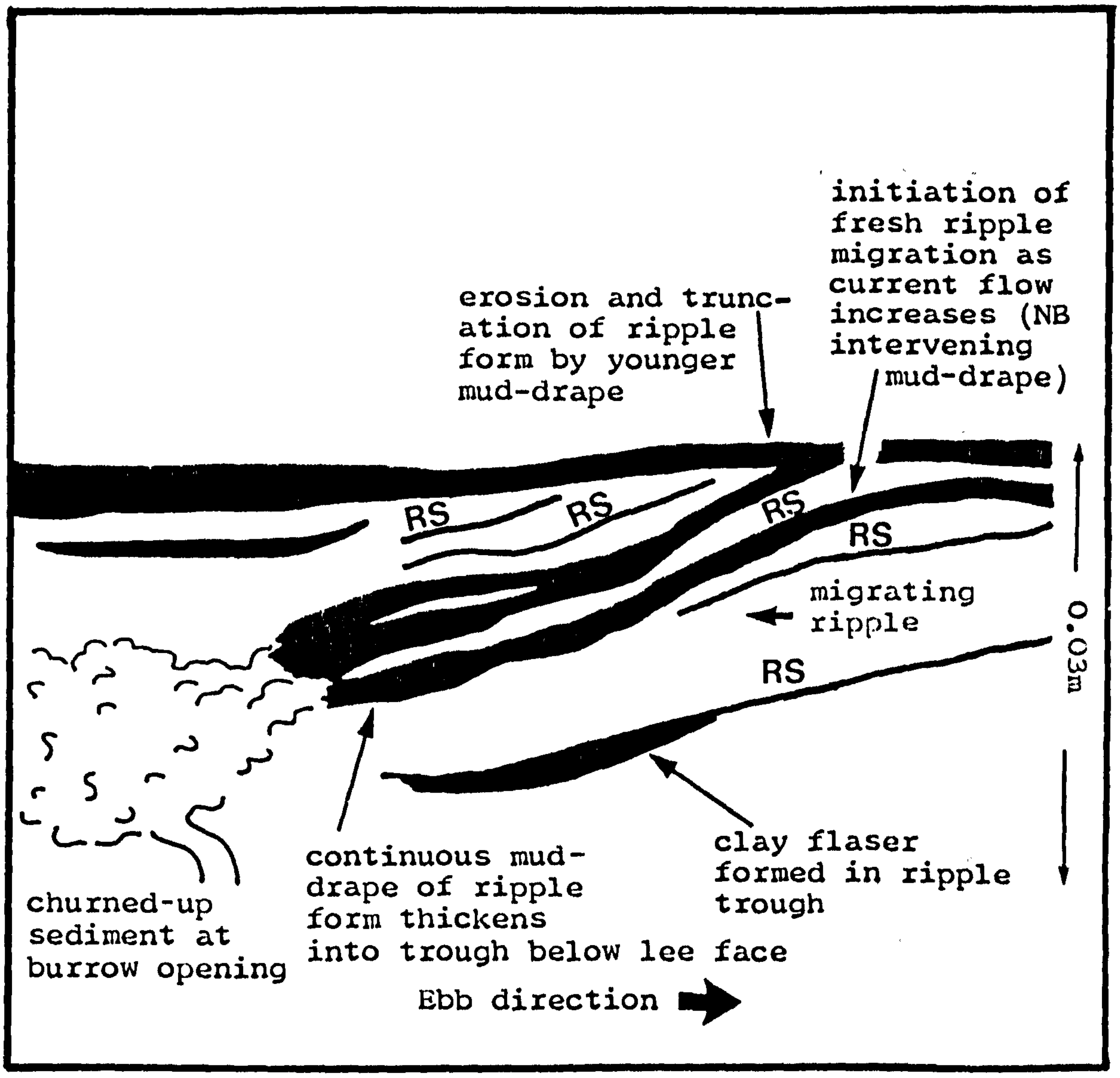


Fig.10.20 Flood-oriented ripple with reactivation surfaces, box-core peel 2, Carsenestock point-bar. RS - Reactivation surface(s), indicating the "stop and start" nature of ripple migration due to fluctuations in current strength. Mud-drapes are products of deposition from suspension

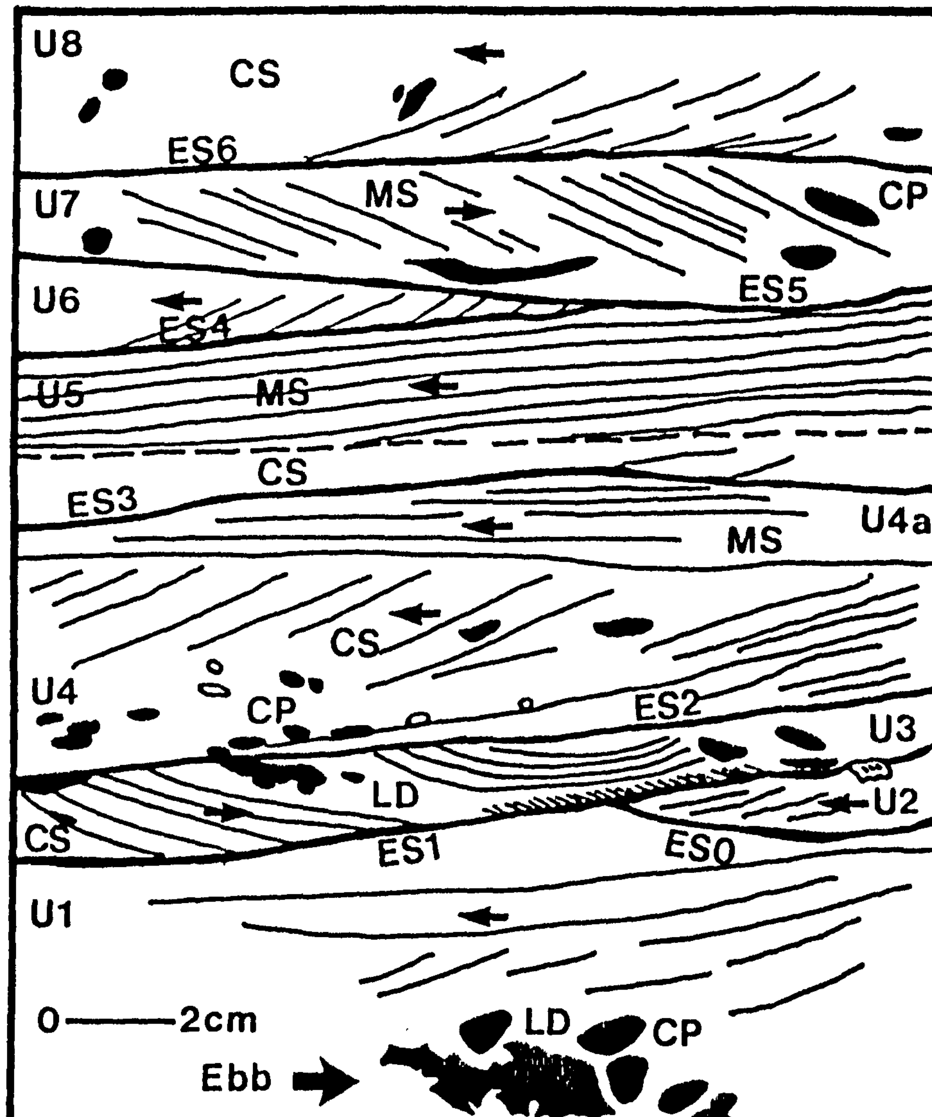


Fig.10.21 Sketch of box-core peel 4, Carsenestock to show salient features. U - Units of flood/ebb reversal, ES - Erosion surface, CS - Coarse sand, MS - Medium-grade sand, LD - Leaf debris, CP - Clay pebbles, flat well-rounded discs, vaguely imbricated. Flood laminae exhibit a low-angled dip c. 10°, ebb laminae exhibit a dip of c. 30°. Arrows indicate flood/ebb direction

floor conditions. The basal 0.02m of unit 1 (see Fig. 10.21) is illsorted; coarse sand, leaf and clay pebble debris has been dumped by a waning current. The remainder of the unit, c. 0.03m thick, exhibits vague flood-oriented planar cross-laminations in coarse sand.

Erosion surface zero (ES0) overlies unit 1 and is followed by unit 2, composed of flood-oriented planar laminae cross-sets, dipping at 15°. Individual laminae are c. 2 - 3mm in thickness.

Unit 2 is overlain by erosion surface 1 (ES1), which exhibits a relief of 0.01m from right to left across the box-core. The erosion surface is overlain by unit 3, comprising ebb-oriented, cross-ripple laminations in coarse sand, which have asymptotic bases. Individual inclined laminae are c. 1 - 2mm in thickness. Wood fragments and clay pebbles are present on the inclined surfaces.

A major erosion surface (ES2) truncates the ebb-oriented unit 3. The surface is overlain by a relatively-thick flood-oriented unit in coarse sand (unit 4). Laminae cross-sets dip at 15° - 20° and have fine-gravel grade mud clasts at their bases.

There then follows an erosive break overlain by a unit (4a) of medium-grade sand exhibiting low-angled (c. 2°) planar cross-laminations. This unit may represent migration of a super-imposed ripple formed during the same flood-tide flow as unit 4, but under lower-stage conditions, or it may be a flood unit formed by the next succeeding flood tide following deposition of unit 4, the intervening erosion surface between units 4 and 4a therefore representing an erosive ebb break.

Erosion surface three (ES3) is overlain by another major flood-oriented ripple migration unit (5). Vague flood-oriented planar cross-sets in coarse sand fine upwards to thinly plane-laminated medium sand; laminations are gently inclined and c. 1 - 2mm thick. The unit represents a waning current with "lower flow regime" plane laminations.

In contrast, the overlying unit, 6, which lies above erosion surface 4 (ES4), exhibits quasi-asymptotic-to-the-base, curved, flood-oriented laminations, indicative of sinuous ripples. Cross-set laminae are inclined at c. 30° and are formed in medium to slightly-coarse sand. The overlying erosion surface five (ES5) down cuts from unit 7 to 5, therefore truncating unit 6. It is overlain by unit 7, which consists of ebb-oriented planar cross-laminations a few millimetres thick. Inclined claypebbles, c. 0.01m in length, are evident within the unit.

Erosion surface six (ES6) is horizontal, or nearly so, and is overlain by a flood-oriented unit (8) composed of coarse sand. Cross-laminations exhibit almost asymptotic bases (hence ripples are sinuous) and are inclined at 30°. Mud pebbles are present within the unit.

General examination of box-core peel 4 indicates that there are more flood than ebb episodes represented, and therefore flood deposition is likely to be predominant. It appears that the flood tide persistently wipes out all evidence of ebb deposition unless the flood tide is particularly weak. Where ebb-oriented units are preserved, the bounding lower erosion surfaces are laterally persistent. This implies strong erosion, followed by active deposition against a relatively weak opposing flood tide. Such conditions could occur during periods of high fluvial discharge and/or during neap tides, when the flood tidal cycle is weak.

Box-core Peel 5 - chute-channel, mid point-bar

Only the lowermost 0.13m of the original box-core sample was successfully impregnated with epoxy-resin due to the non-cohesiveness of the coarse to very coarse sand. The upper part of the sample was lost. The coarseness of the sand also had prevented the formation of clearly discernible sedimentary features. This was also the case in box-core peel 7. Box-core peels 5 and 7 are composed of coarse to very coarse sand because of the superimposed influence of channel processes in the immediately adjacent channel of the River Cree.

The basal 0.02 to 4.5cm of box-core peel 5 consists of coarse sand with poorly-developed flood-oriented planar foresets inclined at c. 20° - 25°. Imbricated, well-rounded and flattened mud pebbles are evident, as is a twig aligned length-parallel to the current direction. Deposition of sediment was fairly rapid.

There then follows c. 0.02m of gently-inclined planar laminations in slightly less coarse sand.

This unit is overlain by 0.01m of ebb-oriented planar foresets with laminations inclined at 15° and followed immediately by a reversed flood-oriented unit c. 0.02m thick. Both units exhibit a typical herringbone pattern of cross-stratification.

Upwards, there follows a repeated herringbone unit and, at the top of the box-core peel, a final 0.04m thick flood-oriented unit of planar cross-stratified laminae, inclined at 20°.

In summary, box-core peel 5 exhibits an overall high level of environmental energy with reversal of currents in a tidal situation as exhibited by the herringbone cross-stratification.

This pattern is repeated in box-core peel 7, now described.

<u>Box-core Peel 7</u> - chute-channel margin/River Cree channel junction

Box-core peel 7 consists mainly of coarse sand units deposited under high energy conditions. Fluctuation in environmental energy is evident in the topmost 0.06m of the box-core in the form of mud flasers and silty drapes, deposited from suspension under a low velocity current.

The basal 0.04m of the box-core peel consists of coarse sand which exhibits flood-oriented planar cross-stratification with laminations inclined at 10^{o} - 15^{o}.

This sand unit is overlain by 0.04m to 0.065m of very coarse sand exhibiting poorly-developed gently-inclined flood-oriented laminations c. 1 to 2mm thick. Also preserved is a small amount of lag debris, consisting of a rod-shaped mud pebble with its long axis oriented parallel to current direction, together with fine gravel-grade quartz grains, leaf remains and shell fragments. A single Cerastoderma edule valve is present with its umbo oriented upstream and the valve in a concave-up position.

The flood-oriented plane laminations probably developed under upper flow regime conditions under a high velocity current. Sediment has been rapidly deposited, as the Cerastoderma edule valve is not in the most stable of positions.

The very coarse sand unit is overlain by c. 0.02m of poorly-developed, gently-dipping (5^{o}) flood-oriented laminations, c. 1 to 2mm thick.

Above this unit there is evidence of a sudden decrease in environmental energy, provided by a thin layer of medium sand overlain by a 0.01m thick, horizontal layer of leaf debris deposited during a lull in flow-energy conditions.

The leaf layer is also overlain by a thin layer of medium sand which grades upwards into a layer of coarse sand, c. 0.01 to 0.02m thick. The coarse sand exhibits poorly- to well-developed horizontal laminations c. 1 to 2mm thick, formed under high flow regime conditions. These conditions appear to have been followed by a sudden decrease in energy allowing for the formation of a mud flaser, the mud being deposited from suspension in a ripple trough. The ripple is flood-oriented and its poorly-developed cross-sets were recorded below the flaser.

The flood-oriented plane laminations are abruptly truncated by a thin overlying ebb-oriented unit of coarse sand. Cross-stratified laminae are poorly-developed, but ripples were recorded as infilling and migrating over the mud flaser developed in the underlying ripple trough.

The ebb-oriented unit is overlain by a very thin silt to fine sand drape.

The drape in turn is overlain by a further ebb-oriented unit exhibiting small-scale migrating ripple forms present in medium-to-slightly-coarse sand. Cross-stratified laminae are inclined at approximately 10^{o}. Their bases are gently asymptotic. The ripple troughs are infilled with silty mud, forming well-developed flasers. The latter are overlain by gently-dipping (5^{o} - 8^{o}) flood-oriented cross-stratified laminations in medium-to-coarse sand. Mud pellets are present at the base of the unit.

Outlined below is a summary of the main characteristics of the Carsenestock point-bar. A fuller conclusion regarding the point-bar and previously described side-bars is presented in Chapter 10.2.5.

<u>Characteristics of the Carsenestock point-bar; a summary</u>

<u>Upper point-bar</u> (boxes 3 and 6)

1. Composed predominantly of fine sand that is loosely consolidated.

2. Good preservation of flood-dominant sedimentary structures.

3. Structures such as sand/mud couplets show repeated changes of environmental energy, with distinct separation of high energy flood deposition of

sand ripple units, and low energy deposition of mud from suspension.

4. Evidence of post-depositional deformation, with fluid-ejection features and folding of sediment.

<u>Mid, upper point-bar</u> (boxes 1 and 2)

1. Composed of equal amounts of sand and mud sediment, which is more compact than the sediment of the upper point-bar.

2. Thin alternating layers of mud and sand indicate rapid fluctuation of environmental energy, the mean of which is slightly higher than that of the upper point-bar.

3. The ripple phase of the sand units is not as well developed as that of the upper point-bar.

4. Bioturbation is evident in the mud intervals.

5. Re-activation surfaces indicate the intermittent nature of deposition.

<u>Chute-channel, mid point-bar</u> (boxes 4, 5 and 7)

1. Composed predominantly of medium to coarse sand, with some very coarse sand, generally loosely consolidated.

2. Absence of mud.

3. Abundant typical channel-floor lag debris such as leaf and twig fragments, shell fragments and well-rounded, flattened clay/mud pebbles. Lag debris is frequently imbricated in the prevailing flood-or ebb-current direction.

4. Repeated reversal of flood-and ebb-oriented cross-sets, forming herringbone cross-stratification, indicative of the reversal of currents in a tidal situation.

5. Environmental energy is consistently higher than in other areas of the point-bar.

6. Presence of more flood-oriented cross-sets than ebb-oriented features, indicative of predominant flood-oriented deposition during strong flood tides. Conversely, the ebb is relatively weak, unless river discharge is high.

7. Gently-dipping planar laminations (the majority of which are flood-oriented) indicate frequent periods of upper flow regime conditions.

10.2.5 General Conclusions

Study of the sedimentary structures and textures of differing types of large-scale bars in the upper Cree estuary shows that a close relationship exists between textures, structures, influence of rivers and the energy of the environment. Estuarine substrates are dynamic. Currents capable of transporting coarse to very coarse sand and gravel grade sediment are evident in the upper reaches of the estuary. Small-scale scour horizons are widespread, both laterally and vertically.

The physical and biogenic sedimentary structures of the upper Cree estuary are similar to Dorjes & Howard's (1975), "inner estuarine facies" characterised by the following features:

1. Mid-channel and side-bars exhibit large-scale cross-beds (megaripples) with a downstream dip direction due to the fluvial character of the river, despite location in an area of tidal influence. Ebb/flood reversals producing herringbone cross-stratification are evident in chute-channel sediments of the Carsenestock point-bar. It is not known whether or not main channel-floor bar sediments downstream of this location bear unidirectional large-scale cross-beds due to the diminishing influence of the fluvial flow compared with that of the tide in a seaward direction. It _is_ known, however, that at Creetown a mid-channel bar exhibits bidirectional cross-beds, _i.e._ herringbone cross-stratification.

2. Orientation of sedimentary structures may vary because of the sinuousity of the meanders. This is true of a point-bar situation and is also found in channel-flank and channel-bar environments when secondary, superimposed sedimentary features form as a result of late-stage draining by the ebb current. Features are persistently oblique to, or at right angles to the general ebb-current direction. Interference of flow is common, resulting in a complexity of sedimentary structures.

3. Other structures include small-scale ripple laminations and sand/mud alternations. These are formed predominantly in a point-bar situation where mud and sand proportions are more or less equal. They are present, however, in a channel-flank environment but are generally poorly-developed since channel-flanks are mostly composed of clays and fine-grained silts.

4. Channel lag debris, including clay clasts, flat mud pebbles and occasional beds of quartz pebbles, is present. Some quartz beds show faint traces of stratification but this is generally difficult to define due to the size of the grains. Fine mud is absent.

   Coarse to very coarse sand is confined to a channel situation. It is "clean", a feature typical of estuaries with rivers at their heads. Although there is a high concentration of "fines" in suspension within the water, these very rarely settle out in a channel environment since current velocities are too high. Therefore, deposition of fine-grained deposits takes place on point-bars and channel flanks.

5. Biogenically there is very little disturbance, with only occasional traces of bioturbation, and this is confined to fine-grained point-bar or channel-flank deposits. Presence or absence of biogenic activity

is related to the energy of the current. Ripple-laminated sand (formed under high energy conditions) exhibits a decrease in biogenic structures, whilst mud intervals, corresponding to lower-energy conditions, are subject to an increase in biogenic activity.

10.3 A STUDY OF SMALL-SCALE SEDIMENTARY AND ORGANIC STRUCTURES OF UPPER TIDAL-FLATS AND CREEKS IN THE CREE ESTUARY AT CREETOWN

10.3.1 Introduction

The following account describes the sub-environments of deposition recorded during a box-coring exercise undertaken along the southern bank of the Moneypool Burn and on the adjacent mudflat immediately south of the Burn near Creetown, between locations NX 472 585 and NX 467 585 (Fig. 10.22). The exercise involved an E to W transect of the intertidal marsh (Figs. 10.22 and 10.23), sampling being undertaken at the margin of the channel (box 6) and migratory point-bars (boxes 7,8,10). Box 11 represents a mixed-flat setting, whilst boxes 12 to 14 were sited along the crest of a 250m long sand-bar, lying parallel to the main current flow of the River Cree. Box 15, representative of a sand flat setting, was located off the crest of the sand-bar. Box 16 was positioned in the erosional scour depression east of the landward flank of the sand-bar.

A study of aerial photographs of the Moneypool Burn and its adjacent area provides the basis for, (a) reconstructing the pattern and estimating the rate of migration of the channel of the Burn and, (b) tracing marsh/mudflat construction and destruction, over a period of 38 years, from 1946 to 1984.

From a study of the box-cores it is also possible to estimate rates of erosion and deposition in specified sub-environments.

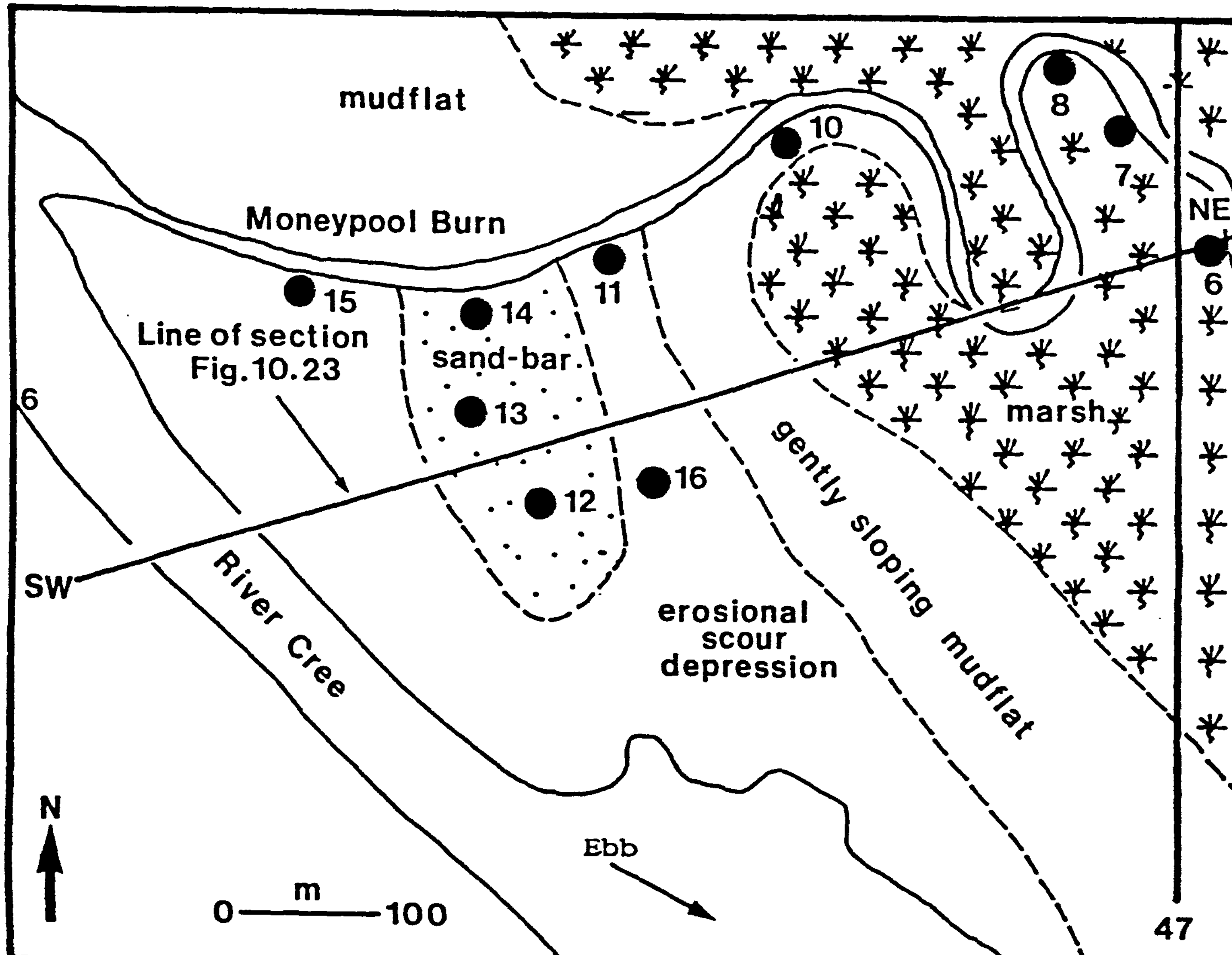


Fig.10.22 Map to show position of box-cores, Moneypool Burn, Creetown.
NB Box-cores are numbered

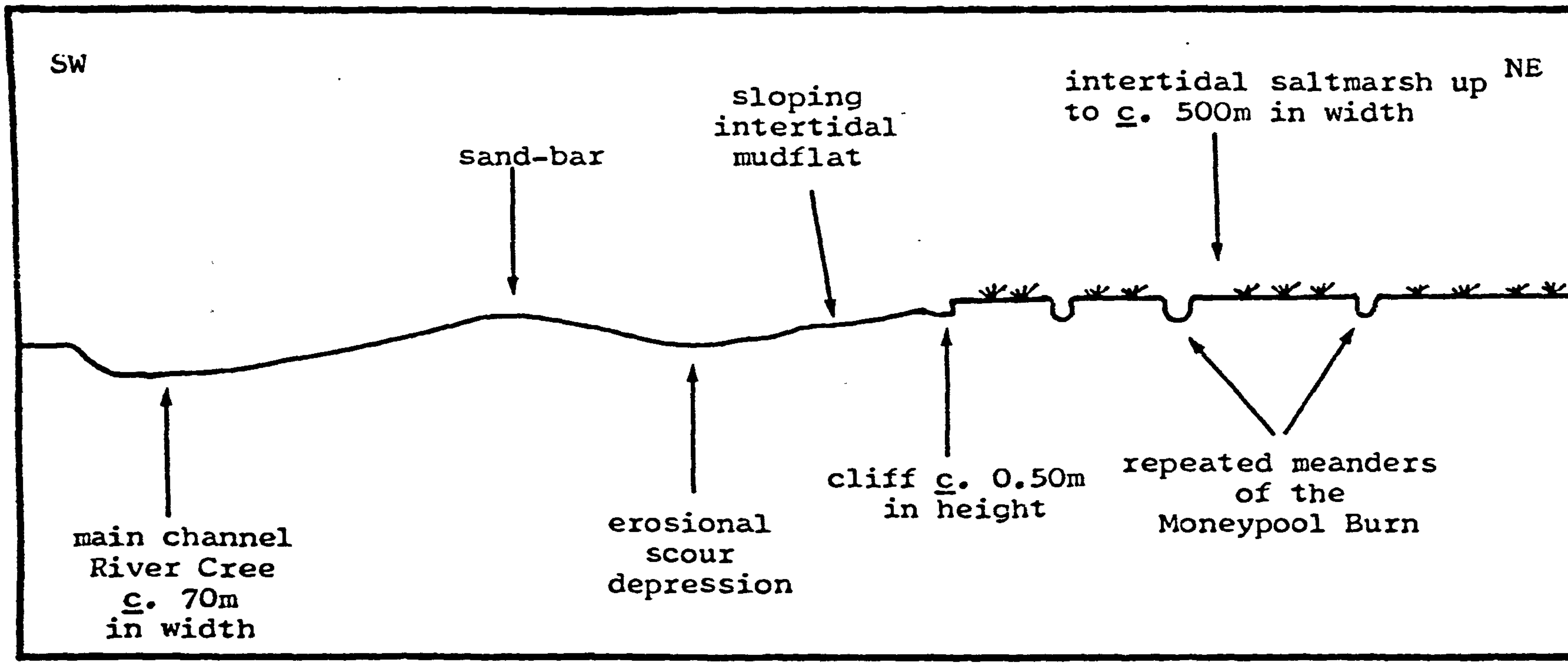


Fig.10.23 South-west to north-east section across the intertidal marsh to the main channel of the River Cree near Creetown. NB Scale SW to NE 900m

The results of analysis of sedimentary structures and organic features recorded in the box-cores are discussed in relation to environment and physical energy.

Finally, a microsequence is proposed, with the aim of establishing the occurrence of tidal-flat sequences in the ancient record, and inherent problems are discussed.

10.3.2 Physiography and sub-environments of deposition

The area studied (Fig. 10.22), approximately 1km x 0.5km in dimension, is located west of Creetown at the confluence of the Moneypool Burn and the southerly-flowing River Cree. It is covered at times of high spring tides. At low water, a 1km wide belt of intertidal flat is exposed. The maximum altitude of the surface area is 4.50m A.O.D., there being a gentle slope towards the Cree estuary.

Four morphological sub-zones are distinguished (Fig. 10.22), these being arranged parallel to the course of the main river and trending NW - SE. Each zone constitutes a recognisable sub-environment of deposition, characterised by distinctive deposits and organisms. A fifth sub-environment occurs, that of a laterally-migrating tidal-creek/point-bar complex, arranged at right angles to the main channel and dissecting the intertidal flat. Smaller-scale tidal-creeks, exhibiting a dendritic pattern of drainage, drain the higher intertidal marsh. The sub-environments are discussed below.

10.3.2.1 Intertidal salt-marsh

The intertidal salt-marsh comprises a c. 500m wide, gently-sloping zone, landward of the adjacent mudflat but below M.H.W.S.T. Its surface is dissected by a dendritic pattern of small creeks. The salt-marsh is divisible into high and low intertidal units. The former extends from M.H.W.S.T. seawards for approximately 250 to 300m and is covered by water at high spring tides only. The salt-marsh surface is cut by small meandering creeks which become shallow inland

and carry no freshwater drainage. The creeks were formed during an early period of marsh construction. Creeks in a zone immediately adjacent to the Moneypool Burn often coalesce and are "captured" by the larger tidal outlet of the Burn. The "low" intertidal salt-marsh, seen predominantly in an area to the north of the Moneypool Burn, extends for c. 250m seawards from a landward boundary with the high intertidal marsh to a cliffed or diffuse junction with the unvegetated mudflat. This junction is the zone of active marsh growth or progradation and also of destruction. The "low" marsh is frequently flooded at high tides. The creek system is intensely dendritic. Creeks frequently merge and enter mudpans which enlarge seawards. The nature of the contact between the marsh and mudflat is dependent on the processes operating at a particular location. If erosion is dominant, the marsh edge is represented by a c. 10 to 20cm step, which may not be laterally continuous, as elsewhere along the marsh/mudflat junction, where depositional processes are in operation, the step may lessen in height and merge into a diffuse contact. A diffuse contact occurs where processes of vertical and lateral accretion lead to mud particles being filtered and trapped by the marsh edge vegetation. Consequently, deposits of the salt-marsh are well-laminated clays and silty clays containing a high proportion of carbonaceous matter, marsh grasses, faecal pellets and occasional shell debris. The process of vertical accretion is responsible for the upward (altitudinal) growth of the marsh. Lateral marsh progradation is brought about by the gradual seaward encroachment of marsh grasses over mud, which forms an interlayering. The position of the leading edge of marsh progradation and erosion is dependent on the energy balance of the environment and is linked with meteorological and sediment-supply factors. Normally winter storms bring about overall destruction of the marsh by erosional processes, whilst progradation occurs under fairweather (summer) conditions.

10.3.2.2 The intertidal mudflat

This area forms a zone, 150m (minimum) in width, which slopes with a surface dip of c. 20^{o} towards the channel of the River Cree. The landward boundary is marked by the marsh/mudflat contact. The seaward margin lies in the erosional scour depression where a transition from mud to sandier sediment occurs. The surface of the mudflat is even, but occasionally is dissected by late-stage drainage features such as rills which flow into the main channel and the scour depression. Deposits of the mudflat are well-laminated silts, clayey silts and fine sands. The sandy laminae decrease in abundance inland with the increasing proportion of mud. Plant material is plentiful, together with a small quantity of mashed shell debris.

10.3.2.3 The longitudinal sand-bar

The sand-bar, located in the main channel of the River Cree, is c. 250m in length and 150m in width and is lozenge shaped. It trends approximately parallel to the main channel (N to S), and is symmetrical in cross-section, with very gently sloping limbs. The landward limb terminates in the erosional scour depression; the seaward limb slopes towards the sandflat adjacent to the subtidal channel of the River Cree. The sand-bar is covered at high water by all tides and is actively migrating. Its northern margin is truncated by erosion and by reworking of the presently southerly-migrating, meandering channel of the Moneypool Burn. The southern end merges with the sandflat at the Scaur fishery nets (NX 467 582). The SW flank of the sand-bar exhibits small shear ripples superimposed on the larger ripples of the sandbank. These are formed by the action of an onshore SW wind.

10.3.2.4 Main channel of the River Cree

The subtidal channel of the River Cree, i.e. that permanently flooded, is 70m wide. Its western bank is bounded by an artificial embankment or breakwater.

10.3.2.5 Laterally-migrating tidal-creek and point-bar complex of the Moneypool Burn, and associated marginal features

The Moneypool Burn, as a result of active incision, lateral migration and reworking, exhibits a complex of well-developed, mature meanders and muddy point-bars, which are now considered.

The Moneypool Burn is tidal to below Barholm Bridge (NX 474 589), and has a partially-braided course downstream from this point to NX 470 586. Along this reach, longitudinal sheet-like bars of pebbly, cobbly gravel, presumably derived from the underlying glacial deposits further upstream, are found along the creek floor. The bars (often only one or two cobble layers thick, i.e. c. 0.20 to 0.30m), are frequently and patchily covered with c. 0.20 to 0.30m thick, water-logged mud, deposited from suspension at slack water.

Along the cut-bank margin at NX 470 586 there occurs a series of tensional fissures (Fig. 10.24) that results from under-cutting and dessication of the bank edge. The fissures are curvilinear and approximately 0.40 to 0.50m in length. They lengthen and join prior to brittle and rotational failure and collapse. Slide blocks are eventually masked by successive periods of mud deposition. The blanketing effect of the mud drapes may aid the preservation of the slide/slump feature as well as helping to preserve the cut bank by slowing down the rate of erosion.

The meandering reach of the Moneypool Burn corresponds approximately with the low intertidal marsh zone (Chapter 10.3.2.1). Meanders are well developed, and the point-bars are muddy and unvegetated. The upper surfaces of the bars are prone to dessication as the ebb water drains, giving rise to polygonal cracks and mud flakes. Additionally, there are numerous grazing trails present, together with bird foot-prints, holes made by pecking in search for food and occasional tufts of rotting vegetation. The point-bar

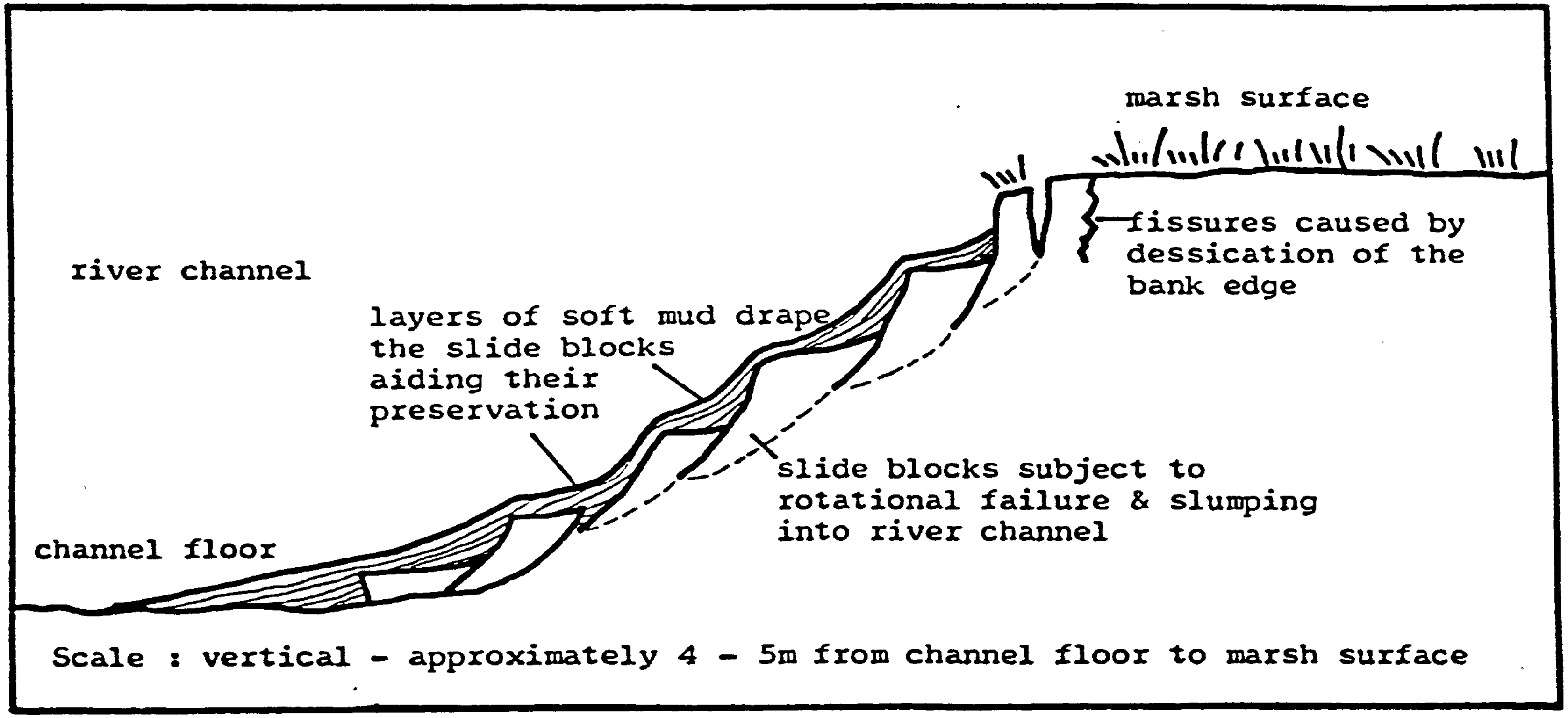


Fig.10.24 Sketch section to show collapse of cut-bank margin, Moneypool Burn NX 470 586

deposits are progressively sandier in a seawards direction. Close to the channel-margin and on the point-bar fronts the muddy and sandy deposits are highly unstable. This instability presented difficulties when sampling of the structures located in the creek base and at a lower level on the point-bars was attempted.

10.3.3 Pattern and rate of migration of the Moneypool Burn, 1946 - 1984

10.3.3.1 Introduction

During the past 38 years there have been significant changes in the position of the channel mouth of the Moneypool Burn, where it enters the main channel of the River Cree. The large tidal-creek has been subjected to several phases of predominantly-northward lateral migration as a result of lateral accretion of point-bars and construction of a northward-moving longitudinal sand-bar. Periodically the sand-bar is destroyed by limited southward migration of the creek channel. However, this southward movement is short-lived, the northward trend of lateral migration persisting due to the heavy bias towards flood-tide dominated deposition of material from suspension.

Evidence for the changes mentioned above was obtained from the study of Ordnance Survey maps and aerial photographs, the latter available at reasonably regular intervals from 1946 to 1978. The present-day situation was monitored on site. Former positions of the Moneypool Burn channel and marsh/mudflat margin were traced from the air photographs and superimposed (Fig. 10.25). Approximate rates of migration per annum of the shifting channel and marsh progradation or erosion were calculated by dividing the distance of shift by the year interval involved. The data are recorded in Tables 10.1 and 10.2 and discussed below.

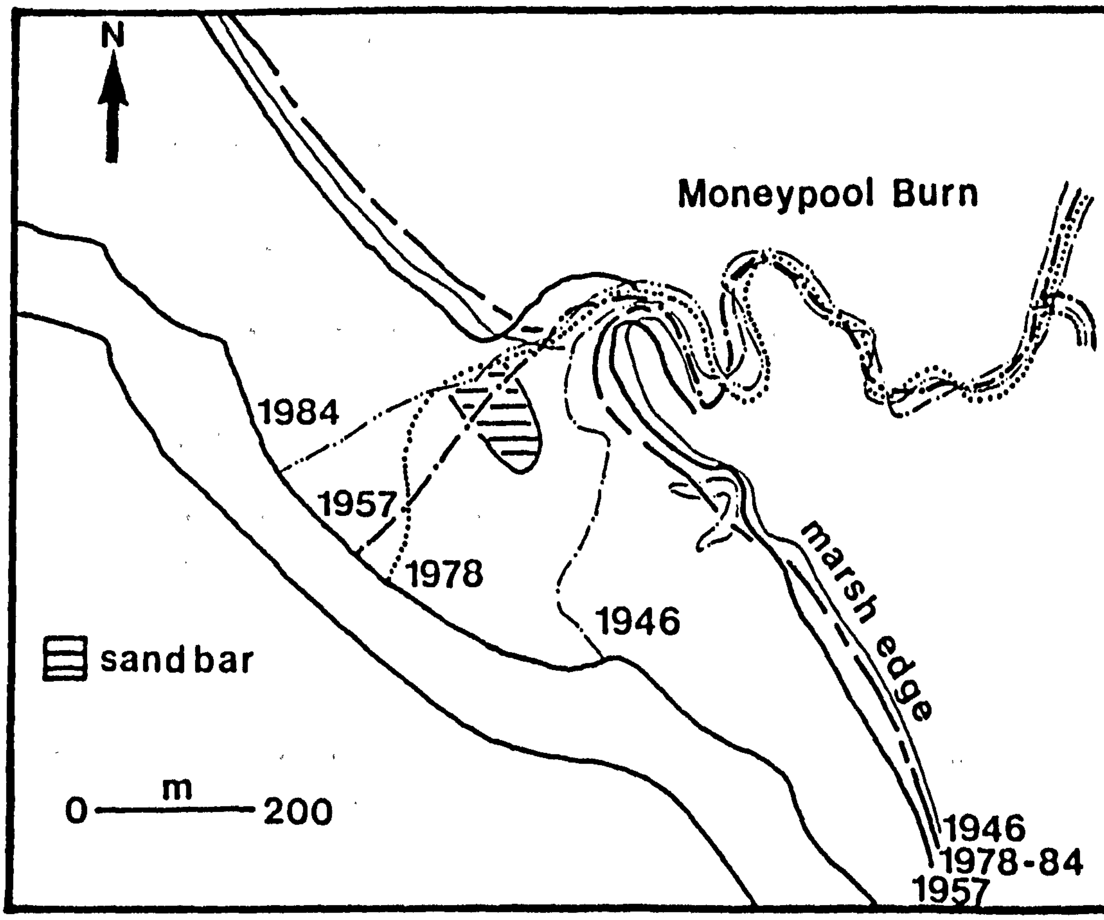


Fig.10.25 Map to show shifting channel and marsh edge positions, Moneypool Burn 1946 to 1984

Year Interval	Distance covered	Average rate of migration per annum
1946 - 1957	210m	19m
1957 - 1978	60m	2.85m
1978 - 1984	120m	20m

Table 10.1 Northward rate of migration of the Moneypool Burn channel, 1946 to 1984

Year Interval	Average distance per annum
1946 - 1957	2.8m (Progradation)
1957 - 1978 1957 - 1978	1.42m (Regression) 1.66m (Progradation of the marsh edge, point-bar)
1978 - 1984	No significant change since the 1978 data

Table 10.2 Marsh progradation/regression rate, 1946 to 1984

10.3.3.2 History and pattern of migration of the Moneypool Burn, 1946 to 1984

Braided reach of the Moneypool Burn

Immediately downstream from the NTL, migration is negligible. The braided portion of the Burn shows increasing sinuosity downstream, with elimination of a mid-stream bar between 1946 and 1957.

Meandering section of the Moneypool Burn

The Moneypool Burn exhibits two well-developed meanders, described below.

i Upper Meander (NX 469 577)

Between 1946 and 1957, this meander migrated downstream by a few metres but shifted upstream again between 1957 and 1984.

ii Lower Meander (NX 468 576)

This more-seaward meander showed significant change between 1946 and 1957, moving 20m downstream during this period. This migration was accompanied by a tightening of the meander loop, associated with northward migration. From 1957 to 1984, the meander has been shifting upstream.

The rate of northward migration of the Moneypool Burn appears to be variable. The true average rate of migration is probably that of 20m per annum, recorded during the smallest year interval period 1978 to 1984 and therefore the most reliable. Ideally, annual changes in channel position should be recorded to gain an accurate estimate of migration rate.

Marsh-edge progradation and regression (Fig. 10.25) are dependent on the availability of sediment within the estuary system at a given location and on the processes in operation. During the years 1946 to 1957, the marsh edge advanced at a rate of 2.8m per annum, during a period when depositional processes and a steady supply of fine sediment dominated.

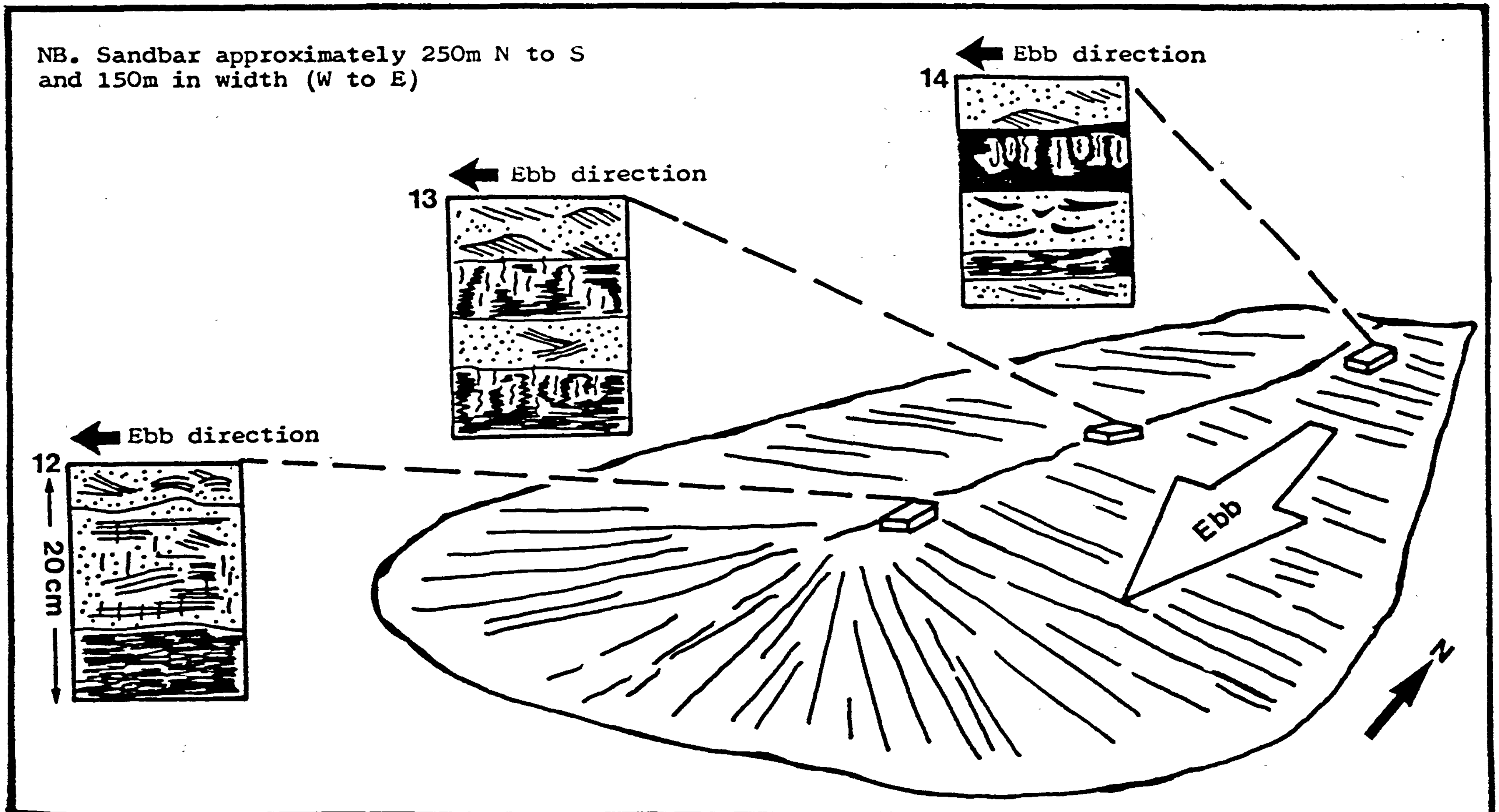
There then followed a period of marsh-edge regression from 1957 to 1978, when the marsh edge receded at a rate of 1.42m per annum. Therefore, marsh regression seems to be half as slow as marsh-edge progradation of the previous 11 years. However, it is probably even slower, since the data for 1957 to 1978 account for a period of 21 years. Whilst marsh-edge regression was occurring along the marsh parallel to the channel of the River Cree during this period, marsh-edge progradation was occurring on the most seaward of the meanders of the Moneypool Burn. Marsh accretion rates were 1.60m per annum. Since then there appears to have been no change in the position of the marsh edge.

10.3.3.3 Rates of mid-channel longitudinal sand-bar accretion and erosion.

Since 1978, the northward lateral migration of the Moneypool Burn has been accompanied by the accumulation of a longitudinal sand-bar in the main channel of the River Cree.

The rate of sand-bar accretion and erosion varies because of fluctuation in the energy of the environment throughout the tidal cycle. High-energy levels are represented by the sandier intervals in the box-cores (Fig. 10.26, boxes 12,13, 14), which exhibit erosive, truncated flood-oriented ripple forms. Ebb-oriented, sinuous ripples were seen to form on the sand-bar surface, but are only occasionally preserved in the box-cores, since they are obliterated by the relatively stronger succeeding flood tide. Sandy-interval accretion rates average 0.02m per day. However, it appears that accretion is greater during the muddy interval (comprising alternating sand and mud lenticular laminae), averaging 0.04 to 0.06m per day. This is probably because the weaker tidal energy of the finer-grade interval allows mud to be deposited from suspension and once deposited, it is difficult to re-suspend. Mud-interval deposition takes place towards the end of ebb-flow conditions and at slack water between tides, and also in quieter phases of the twice-monthly tidal cycle. Sandy-interval accretion occurs both under late ebb- and flood-flow

Fig.10.26 Location of box cores on sandbank, main channel River Cree at the mouth of the Moneypool Burn
NB. Boxes sited along the crest of the sandbank. Boxes exhibit alternations of mud and sand with well-preserved sedimentary structures and evidence of extensive bioturbation



conditions, but only flood-oriented ripples are preserved. Additionally, the gentler tides aid the preservation of ebb-oriented ripples.

As the ebb water recedes, exposing the sand-bar, late-stage drainage rills develop on the bar-flank, at 90^o to the bar crest. The rills are as much as 0.10m in depth and are rapidly incised into the soft bar-flank. Water flow is directed towards the scour depression. Rapid erosion rates are best observed in the scour depression landward of the bar. Shallowing of the water in the depression increases the ebb velocity, thereby increasing erosion rates. Erosion is thought to be rapid, since the depression contains Mya sp. in life position, protruding above the sediment surface. After initial upward movement by the molluscs within their burrows, induced by a sudden influx of sediment, conditions changed rapidly to an erosive setting. The animals had no time to respond and were stranded at the surface. The gaping shells then became choked with sediment, causing the deaths of the animals. The Mya colony consisted of 6 to 8 year-old individuals, normally living at a depth of 0.20 to 0.35m below the sediment surface. Debris, such as branches, twigs, leaves, shells and small pebbles, is stranded on the floor of the erosional scour depression by the rapidly-receding tidal waters. The debris appears to enhance erosion as surrounding sediment is scoured away.

10.3.4. Distribution and structures of characteristic organisms in relation to environment and energy

The modern environment is characterised by a given fauna, which constitutes a biofacies. Upon death, the remains of such a community of organisms are represented by residual hard parts (e.g. shell valves and fragments), structures formed as a result of bioturbation, faecal pellets and organic matter. All these features were recorded in the box-cores, but extensive bioturbation structures predominated.

Bioturbation structures are produced by the activity of living animals, within the sediment or on the sediment surface. Two distinct types of structures are observed, the traces of actual burrows (feeding and dwelling structures), and deformative structures, such as mottling and deflected laminae, caused by animal movement whilst feeding, digging or escaping. The organisms mainly responsible for producing the bioturbation features are the amphipod Corophium volutator and the bivalve Mya arenaria. The distribution of the animals and the structures they produce are a direct result of environmental fluctuations in energy, changes in sediment composition and patterns of erosion and deposition in an intertidal setting. Corophium is concentrated in bioturbated layers that are characterised by periods of deposition of alternating laminae of clay and sand. The abundance of Corophium increases with decreasing water-flow energy, accompanied by a corresponding increase in clay content of the sediment.

10.3.4.1 Areal distribution and structure of organisms

Boxes 6, 7 and 8 (Fig. 10.27) were sited around the southern bank of a migratory point-bar on the upper tidal-flat. The sediment was composed of dark-grey anoxic clays with a considerable carbonaceous component. The high clay content (probably greater than 80%) prevented successful impregnation of the samples with resin. The zone of oxidation extended to a depth of 0.05m from the sediment surface and was of a khaki colouration, as opposed to the dark-grey colour of the anoxic clays. Corophium was abundant and mostly confined to this oxidised zone (particularly in boxes 6 and 8), the straight burrows varying from 0.02 to 0.04m in length and 1 to 3mm in width. In box 7, the burrows were not restricted to the top 0.05m below the sediment surface but occurred in scattered bundles throughout the sample. They were approximately 0.01 to 0.02m in length, 1 to 2mm in width and surrounded by marginal zones of oxidation 1 to 2mm in width. Additionally, box 7 showed extensive mottling below the zone of oxidation, the irregular patches being composed of silt and very fine

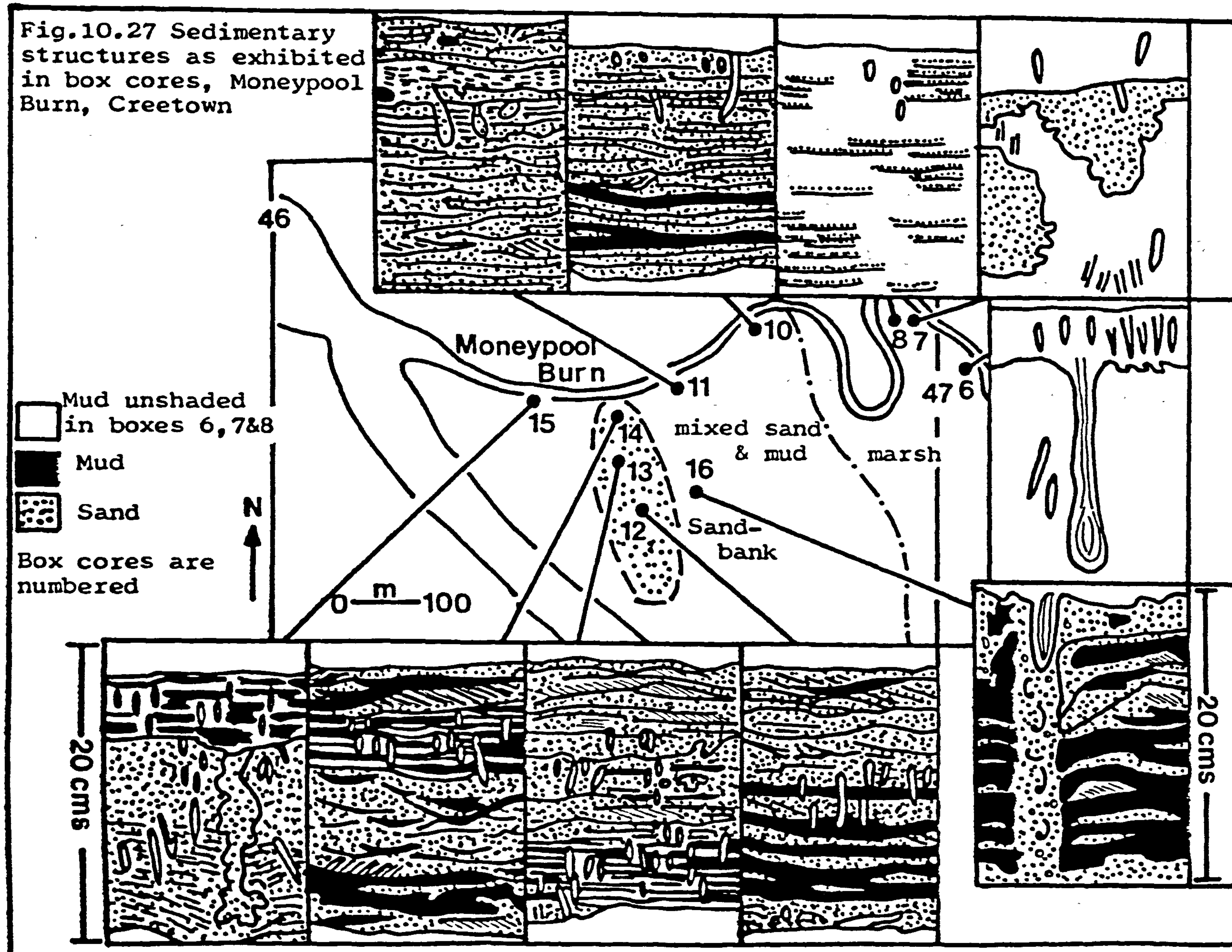


Fig.10.27 Sedimentary structures as exhibited in box cores, Moneypool Burn, Creetown

sand, and the whole feature being a result of intense bio-turbation. Further cleaning of box 6 revealed an individual Scrobicularia sp., 3.75m in length, in life position, the burrow being located at a depth of 19.50cm below the sediment surface. The zone of oxidation extended downwards, around the burrow margins, and was approximately 0.50cm in width at either side.

Boxes 10 and 11 were located as near as possible to the channel margin of the lower intertidal flat. Instability of sediment on the lower point-bar made sampling difficult. There was a significant increase in the sand content of the sediment in these boxes compared with that in boxes inserted in the upper intertidal flat. As a result Corophium was not abundant. However, between 0.04 and 0.10m from the sediment surface in both boxes, there was an interval of alternating clay and sand laminae, containing a few small (c. 0.01m long), scattered burrows. In box 11, the burrows were slightly larger - 0.02 to 0.04m long, 0.01 to 0.02m wide and infilled with coarser, sandy material. It was difficult to determine whether Corophium was responsible for the construction of the last-mentioned burrows.

Box 10 contained minute pits in the sandier laminae. The pits are believed to have once contained faecal-pellet material, which subsequently was washed out. This implies that animal activity is high despite the increasing sandiness of the sediment. Box 11 had abundant organic wisps of grassy material and, at 0.06m below the sediment surface, a horizon of finely-fragmented shell material, evidence of the interaction of erosional processes on the intertidal marsh-flat and depositional tidal-flood action.

Boxes 12, 13 and 14 (Figs. 10.26,10.27) were sited along the crest of a longitudinal sand-bar, 250m in length. The environment represented by the sand-bar is one mainly of high energy, attested by the presence of both simple and bifurcating sandy, flaser bedding which alternates with slightly lenticular beds comprising clay and sand laminae, representing a period of quieter deposition. It is in the latter layers that intense bioturbation occurs. In comparison, the flaser beds are completely devoid of burrows. Whilst these beds accumulated, energy conditions were constantly changing and were not conducive to burrowing. In boxes 12, 13 and 14, there is a prominent muddy interval and bioturbated layer located between 0.05 and 0.10m below the sediment surface. Corophium is abundant, its burrows long (0.01 to 0.05m) and straight, the burrowing keeping pace with sedimentation. Burrows are occasionally U-shaped, with spreiten. In the basal 0.04m of box 12, there is a poorly-defined collapsed burrow, infilled with a sandy "breccia" derived from the downward deformation of the surrounding sandy layers. Box 13 has an additional lower zone of bioturbation between 0.12 and 0.18m below the surface, again with an abundance of Corophium.

Box 15 (Fig. 10.27) sited off the crest of the bar, has two intervals of bioturbation connected by the long escape burrow of an unidentified animal. The lower interval, between 0.12 and 0.20m below the surface, is of compact, alternating mud and sand laminae. Animal disturbance has caused brittle fracturing, leading to the production of micro normal and reverse faults within the cohesive sediment. The upper interval of bioturbation, in the top 0.05 to 0.06m, contains very abundant Corophium, the burrows averaging 0.01 to 0.02m in length and 1 to 2mm in width. At 0.06m, there is a prominent erosion surface, truncating a vertical burrow. The animal which formed the burrow is not present. Initial downward movement into the compact sediment has caused deformation, deflection and fracturing of the sediment. With the influx of sand, the animal moved upwards to keep pace with sedimentation. Sudden erosion then swept the animal away prior to the deposition of mud. The burrow infill is of coarse sand.

Box 16 (Fig. 10.28) was sited in the erosional scour depression on the landward side of the sand-bar. It contained a specimen of Mya at the top of its burrow, projecting above the sediment surface. Earlier burrowing movement by the animal has caused deformation and downward deflection of perfectly-preserved flood-oriented, sandy ripple units. The deflection has resulted in the formation of a distinct burrow nucleus, flanked on either side by a burrow halo (Fig. 10.29). The burrow nucleus is infilled with coarse sandy and shelly material, angular quartz grains and carbonaceous flecks. The top 0.05m of the sediment sample is of a similar composition. The escape of the Mya probably coincided with the influx of coarse-grade sediment, as the mollusc strived to maintain its optimum distance from the sediment surface. The sediment has since been eroded to reveal the Mya at the surface of the erosional scour depression.

10.3.5 Proposed vertical microsequence for a laterally-migrating tidal channel within the general sequence of tidal-flat deposits.

10.3.5.1 Introduction

Tidal-flat deposition is characterised by horizontal or near-horizontal sand and mud alternations. If the flats are dissected by laterally-migrating tidal channels, the bedding produced lies parallel to the current direction and is therefore called longitudinal cross-bedding. Point-bar deposition on the convex side of shifting channels takes place laterally, beds being inclined towards the channel, steepness or gentleness of dip depending upon the size of the bar and the composition of the sediment deposited. The sequence generated by such a lateral migration has been summarised by Reineck (1967). However, it is suggested that Reineck's sequence is too simplified and, in fact, there can be recognised a microsequence that includes several slump units formed by channel undercutting processes (Figs. 10.30 and 10.31).

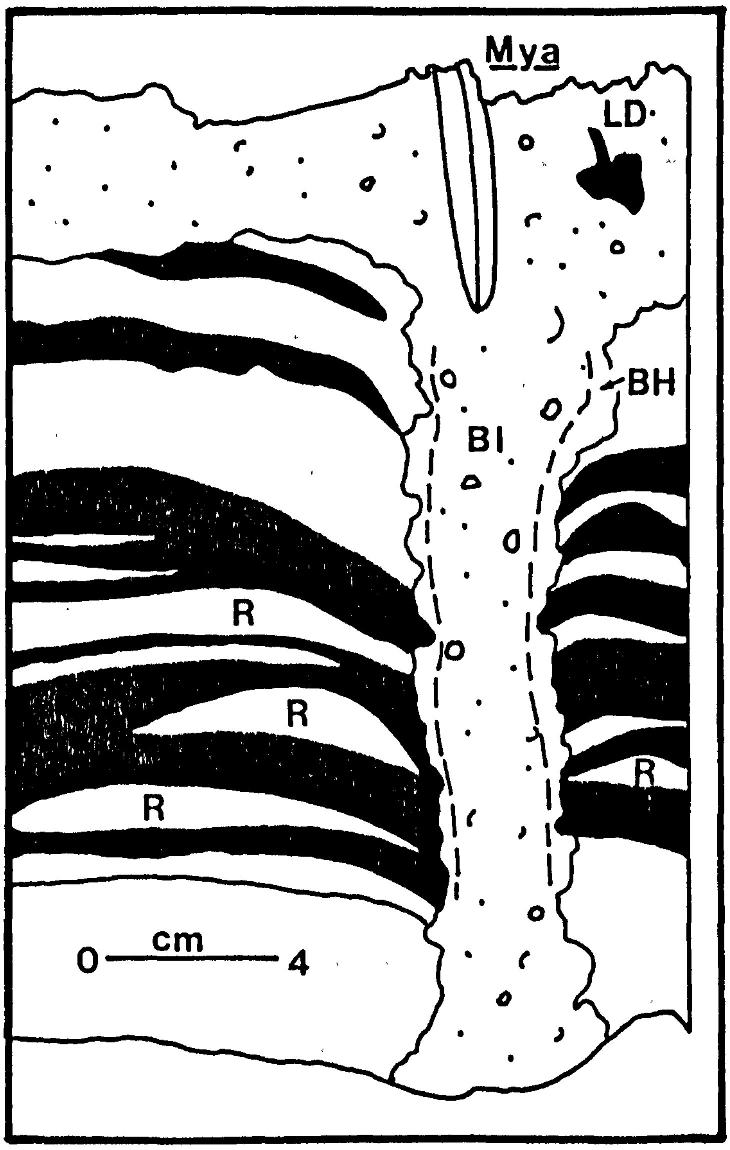


Fig.10.28 Sketch of box-core 16, Moneypool Burn. LD - Leaf debris, BI - Burrow infill, BH - Burrow halo, R - Ripples in sand, mud is black. Ebb direction to the right

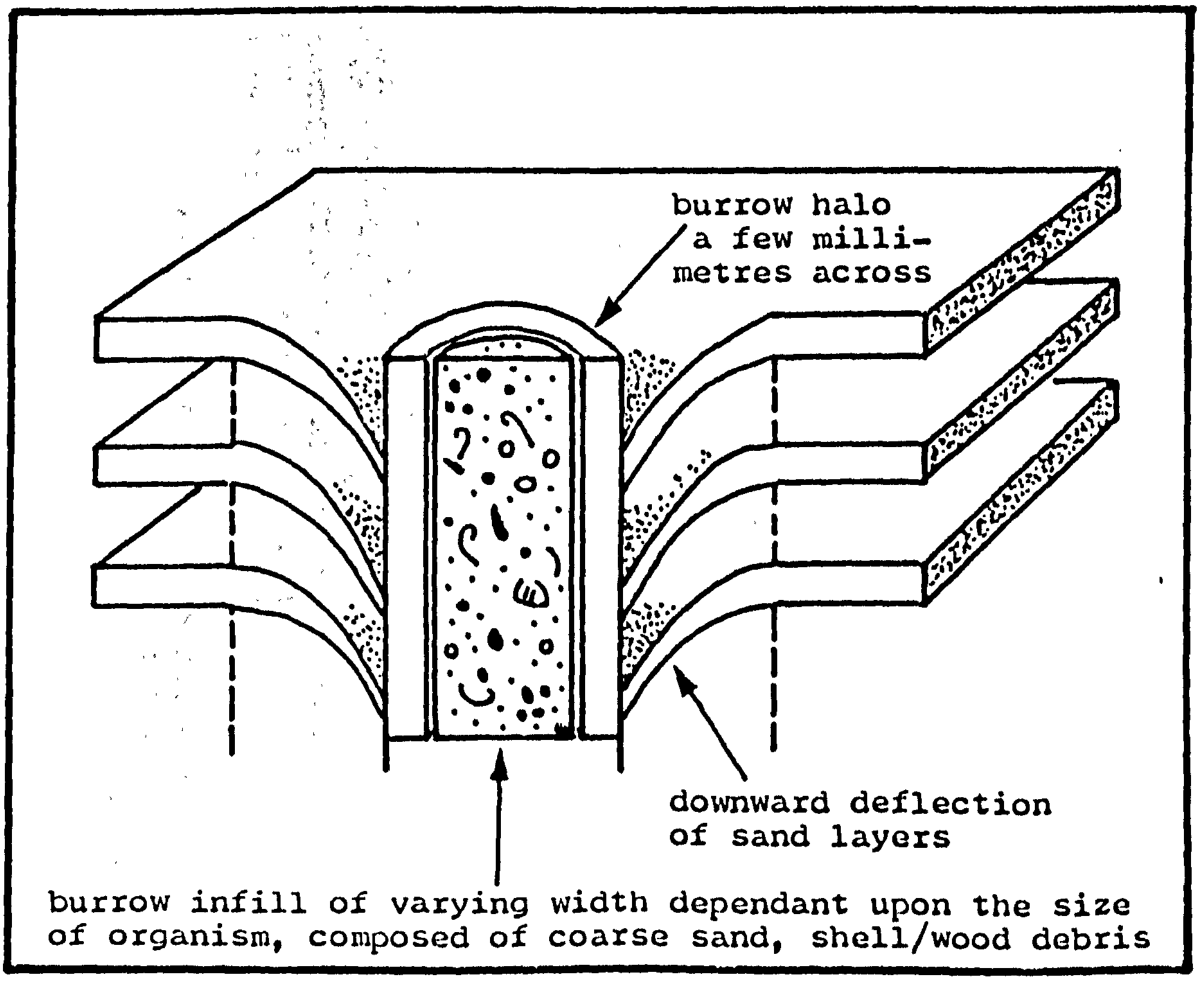


Fig.10.29 Burrow halo formation and downward deflection of sand layers, box-core 16, Moneypool Burn. NB Sand layers alternate with silts and mud

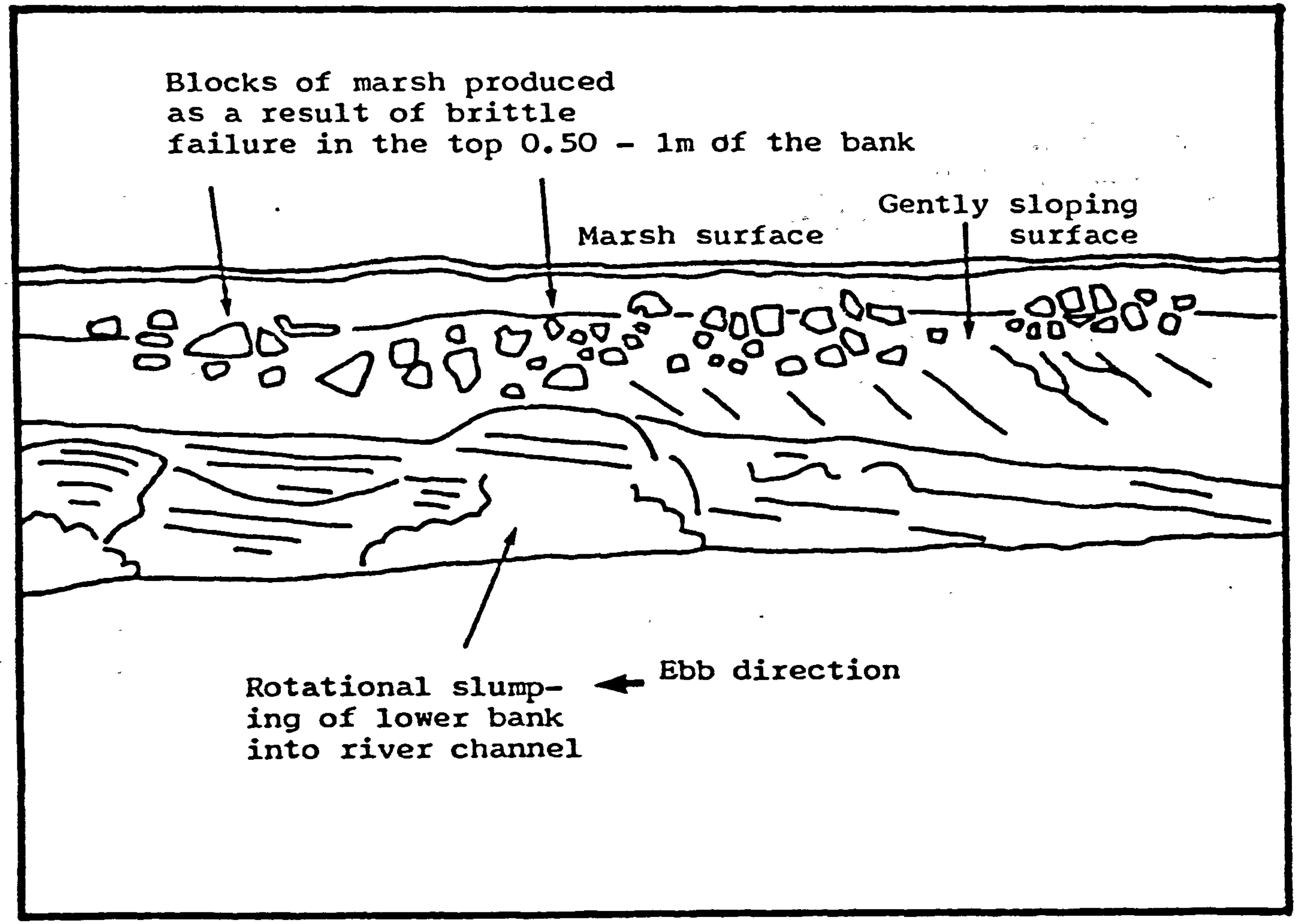
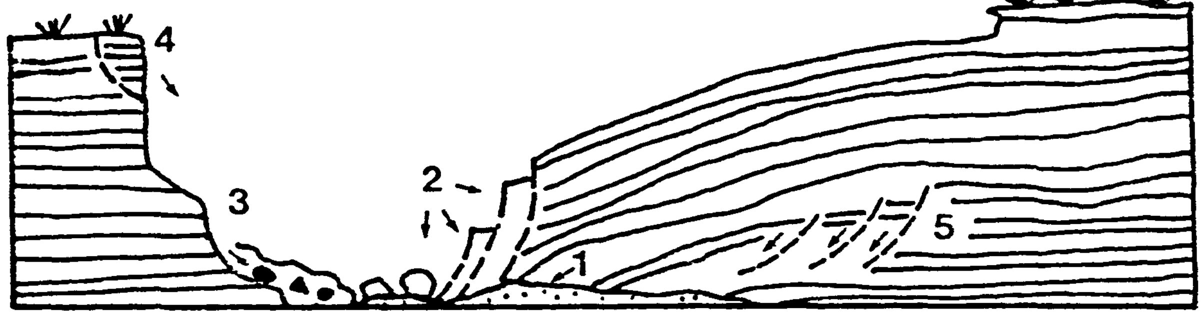
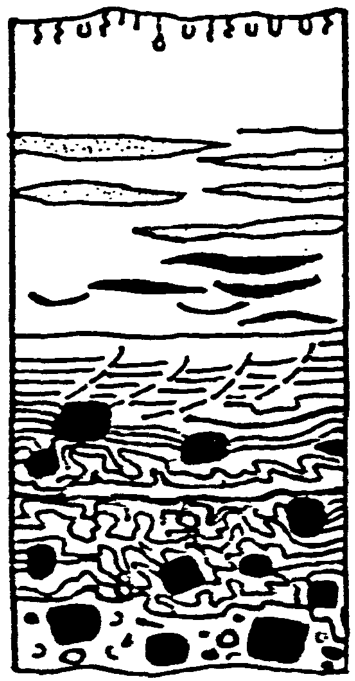


Fig.10.30 Slumping along the outer bank margin, Moneypool Burn





	Process	Structures/Environment
	Bioturbation	Burrows, point-bar surface
	Vertical accretion	Structureless mud, point-bar
	Ripple migration	Lenticular sand, point-bar
	"	Flasers, point-bar
5	Rotational sliding	Faults, deeper level point-bar
3,4		
Erosion		De-watered sand, deeper level point-bar
3,4	Slumping	Folds, basal point-bar
Erosion		Chaotic blocks and channel-floor lag debris, channel-floor
1,2	Erosion	

Fig.10.31 Section across a laterally-migrating tidal channel and micro-sequence generated by such a channel in terms of process and environment

Wetted bank sediments exposed during low water undergo both brittle and plastic failure, producing blocks and slumps. Brittle failure occurs in the uppermost 0.50m to 1m of the cut bank, yielding blocks that are incorporated into the lower units. Rotational sliding also occurs, generally above a fluidised zone that gives rise to convolute bedding. A proportion of the slumped material is taken into suspension. Brittle failure is most likely to occur when the sediment is dried out at neap tides, when the bank may be exposed for lengthy periods, and especially so in summer.

10.3.5.2 Description of the microsequence

A basal erosion surface (Fig. 10.31), corresponding to the creek floor, is overlain by a mud-chip and/or gravel conglomerate of uneven thickness and patchy distribution. The conglomerate is composed of well-rounded clasts eroded from underlying glacial till, through which the creek is incised further upstream. Additionally, the conglomerate contains large pieces of tidal-flat deposits (up to 0.50m in width), derived from faulted blocks eroded from the steep-sided migrating point-bar front. These are typically burrowed, unlike equivalent fluvial deposits. The basal unit is erosively overlain by a plastically-deformed slump which shows convoluted and chaotic bedding. Due to the occurrence of brittle failure in the uppermost 0.50 to 1m of the cut bank (Fig. 10.30), blocks 0.20 to 0.30m in width are yielded, and are incorporated into this lower slumped unit. The unit in turn is overlain by an upper slump unit containing derived blocks. Individual layers are often sheared and may be draped with mud. This uppermost unit is overlain by a zone of brittle failure in the deep-level point-bar, where normal or rotational faults occur. The failure mechanism of the compact, cohesive sediment is generated by the superincumbent load of the point-bar.

The top 2m of the sequence (Fig. 10.31) represents the migrating point-bar which has typical fining-upwards mud and sand alternations. Formation of the latter was punctuated by periods of fluctuating energy, resulting in the production of flaser bedding, the sandier units representing periods of flood-dominated ripple construction and migration. Eventually, the fine sandy material accumulates as isolated lenses which disappear towards the top of the sequence as mud deposited from suspension, becomes dominant. The topmost 0.20m of sediment below the point-bar surface is burrowed by organisms, principally amphipods, most being concentrated in the topmost 0.05m.

10.3.5.3 Conclusions

The sub-environments of the Cree estuary at Creetown, in particular those of the intertidal mudflat, longitudinal sand-bar and laterally-migrating tidal-creek and point-bar sequence (with resulting proposed microsequence) can be described as dynamic. Environments are subjected to constant, repeated erosion and deposition. Lateral migration of tidal-creeks is fifteen times faster than aggradation (G.E. Farrow, pers. comm.). Tidal-flats away from creeks show a predominance of wave-formed structures and flood-oriented ripples alternating with packets of alternating mud and sand laminae. The onset of small herringbone structure is a good guide to tidal-creek (or channel) proximity and provides support for indications of rapid creek migration in tidal-flat areas. Correlation of small sequences over small areas is best achieved by using erosion surfaces (Goldring et. al., 1978).

The bivalve fauna recorded as lag material is likely to be preserved if covered immediately by muds deposited from suspension, as compared with that located in the scour depression, which is highly likely to be washed away if not covered. Additionally, the scour-depression fauna has the high potential of being re-exposed, unlike the channel lag material, thereby reducing the likelihood of complete bivalve preservation. Well-preserved bivalve remains in a channel-floor, channel-infill and low tidal-flat setting were recorded in most of the Holocene sequences.

Bioturbation features recorded in the box-cores should form clearly-defined trace fossils in ancient tidal-flats, although this does not appear to be the case recorded within the Holocene sequence of the Cree estuary area. The reason for this is unknown.

Collapsed, burrowed blocks of tidal-flat sediment form a distinctive and highly preservable record of the migration of tidal-creeks. These disrupted deposits should be at least as common as <u>in situ</u> tidal deposits in inner estuarine palaeo-environments. Examples of plastic deformation and chaotic bedding associated with block collapse were noted in the Holocene stratigraphic record at Muirfad meander and Meikle Carse (Blackstrand and at the east end, immediately south of Meikle Carse farm, see Chapter 5).

10.3.6 General conclusions - preservation potential, recognition of estuarine sediments and environments, and relevance to the Holocene record

Present-day estuarine environments of the Cree estuary area of the Solway Firth, are characterised by repeated aggradation and degradation of tidal-flats and channel sand-bars, and by lateral migration of tidal-channels and creeks with accompanying point-bar construction. Tidal-channel sediments have a high preservation potential. This includes both major and minor tidal-creek infill (<u>e.g.</u> Frey & Basan, 1981). Well-preserved examples of channel-floor and channel-infill sequences within the Holocene were recorded in the Cree estuary area, for example at Meikle Carse and Muirfad meander (Chapter 5) and within the "palaeovalleys" of the Moneypool and Kirkbride Burns (Chapter 7). These sequences are likely to be preserved because of their setting, in an infilling estuary system.

When examining the "ancient" record, apart from evaluating the lateral association of differing neighbouring environments, there is a need to define the elements of the estuarine setting. This is where detailed structures recorded from tidal-flats, creeks and point-bars become significant. Such structures characteristically overlie only estuarine-type sands. It is important to stress that the high tidal energy of the present-day environment is not reflected in an obviously coarse-grade grain size. It appears that this was also true of Holocene times within the Cree estuary area, although the size grade of sediment undoubtedly is generally much coarser now than it was then.

CHAPTER 11 - CONCLUSIONS AND SUGGESTIONS FOR FURTHER WORK

Introduction

Chapter 11 is three-fold. Firstly, in Chapter 11.1, the historical evolution of the Cree estuary area in relation to sea-level change is discussed. This is intended to provide an overview or summary of the past and present environments.

Secondly, a discussion is presented in Chapter 11.2 concerning the extent to which the problems outlined at the start of the thesis in Chapter 3 have been resolved by the research project.

Finally, recommendations for further research work are considered in Chapter 11.3.

11.1 LATE DEVENSIAN TO EARLY HOLOCENE EVOLUTION OF THE CREE ESTUARY AREA IN RELATION TO SEA-LEVEL CHANGE

Background

The position of the Solway Firth coastline varied considerably during the Quaternary Period as a result of eustatic sea-level fluctuations accompanied by localised isostatic adjustments, reflecting the expansion and retreat of several ice sheets. Apparently, all evidence of Tertiary, early- and mid-Quaternary environments has been eradicated by events of the last "main", Devensian glaciation. Evidence relating to the exact position of <u>any</u> Scottish coastline and relative altitude of shorelines is not available prior to 14,000 years B.P. (Price, 1983, p.45). It is thought, however, that immediately before the onset of the last glaciation sea-level was at least 120m lower than at present (Denton & Hughes, 1981, p.311, Price 1983, Fig. 3.2, p.50).

At the maximum of the Devensian glaciation <u>c</u>. 18,000 years B.P., when marine influence was at a minimum, the British coastline perhaps was located near the margin of the present-day continental shelf. The Solway Firth was covered by ice at this time (Price, 1983, Fig. 3.5, p.54 - N.B. this diagram shows the position of the Solway Firth ice margin after 3,000 years of ice build up). According to Penny *et al.* (1969), ice ablation and northward retreat of the ice-front from its maximum, followed by clearance of the northern shore of the present Solway Firth, occurred *c.* 13,000 years B.P. due to a sudden climatic amelioration, from cold to very warm conditions (Coope, 1975), thus accelerating the melting of the Late Devensian ice mass. Furthermore, Coope states that the expected consequent rise of sea-level did not occur and that, from *c.* 14,000 years B.P. to 10,000 years B.P., relative sea-level fell, the rate of isostatic rebound being greater than that of the eustatic rise of sea-level. According to the British Geological Survey (see explanation of sheet 4E for Wigtown), ice ablation did not occur until 12,000 years B.P., when fully-developed interstadial conditions existed. Pantin (1977) records the presence of lagoonal and tidal-flat sediments in the Wigtown Bay area at this time.

As the last remnants of Scottish ice melted and elsewhere, globally, ice masses became reduced to approximately their present volumes, eustatic rise of sea-level overtook the rate of local land rebound. Marine waters moved landwards producing a lateral shift in marginal marine environments and transforming areas of terrestrial character (chiefly fluvio-glacial type environments) into wide estuarine expanses and associated sub-environments. This major event was the wide-spread Holocene (Flandrian) marine transgression.

History of the Cree estuary area

At the start of the Holocene epoch (*c.* 10,000 years B.P.) sea-level was *c.* 1m above O.D. in Wigtown Bay (Jardine, 1975). The sea encroached into a shallow, boggy alluvial depression as it progressed into the Cree estuary area. There is some evidence that the depression was influenced by marine conditions since the pale grey clays laid down at this time contain foraminifers and shell fragments. The environment was a boggy coastal marsh or very high tidal-flat, possibly comparable with Hageman's (1972) perimarine area in the Netherlands. The perimarine area is defined as an area "where sedimentation and settling took place under the direct influence of the relative sea-level movements but where marine or brackish water sediments are absent" (Hageman, 1972, p.37). The transgression progressed to the head of Wigtown Bay, transforming areas of "old" upper tidal-flats/boggy marsh into lower tidal-flats, with the accumulation of broad expanses of intertidal mud banks (similar to those on the west bank of the Cree around Wigtown at present), cut by rapidly laterally-shifting tidal rivers (such as the palaeo-Cree) and many smaller channels. Similar processes operated in the Palnure Burn area, where active undercutting of tidal-flats is preserved in slumped sections.

It appears that the estuary reached its peak development c. 5,000 years B.P. By then, isostatic recovery was outpacing the rise in sea-level; the sea withdrew and the estuary began to be infilled. By 5,000 years B.P. the tidal-flats were elevated coastal marshes, peat formed and seaward progradation ensued. Infilling of the estuary occurred from the margins towards the central "basin" (Fig. 11.1).

Evidence of older, late-stage upper tidal-flat infill is recorded on aerial photographs (Figs. 11.2 and 11.3), exhibiting typical intertidal-flat type dendritic drainage, similar to that observed north of Creetown at the present day. Abandoned meander scars are also evident in the Palnure Burn area (NX 450 630). All these features are located at altitudes which are presently c. 8m A.O.D., due to incision of the infilled area as a result of increased isostatic recovery. More recent remnant meander scars also flank the River Cree (e.g. SW of Muirfad). The infill sediments of the upper River Cree estuary (as a result of incision) are

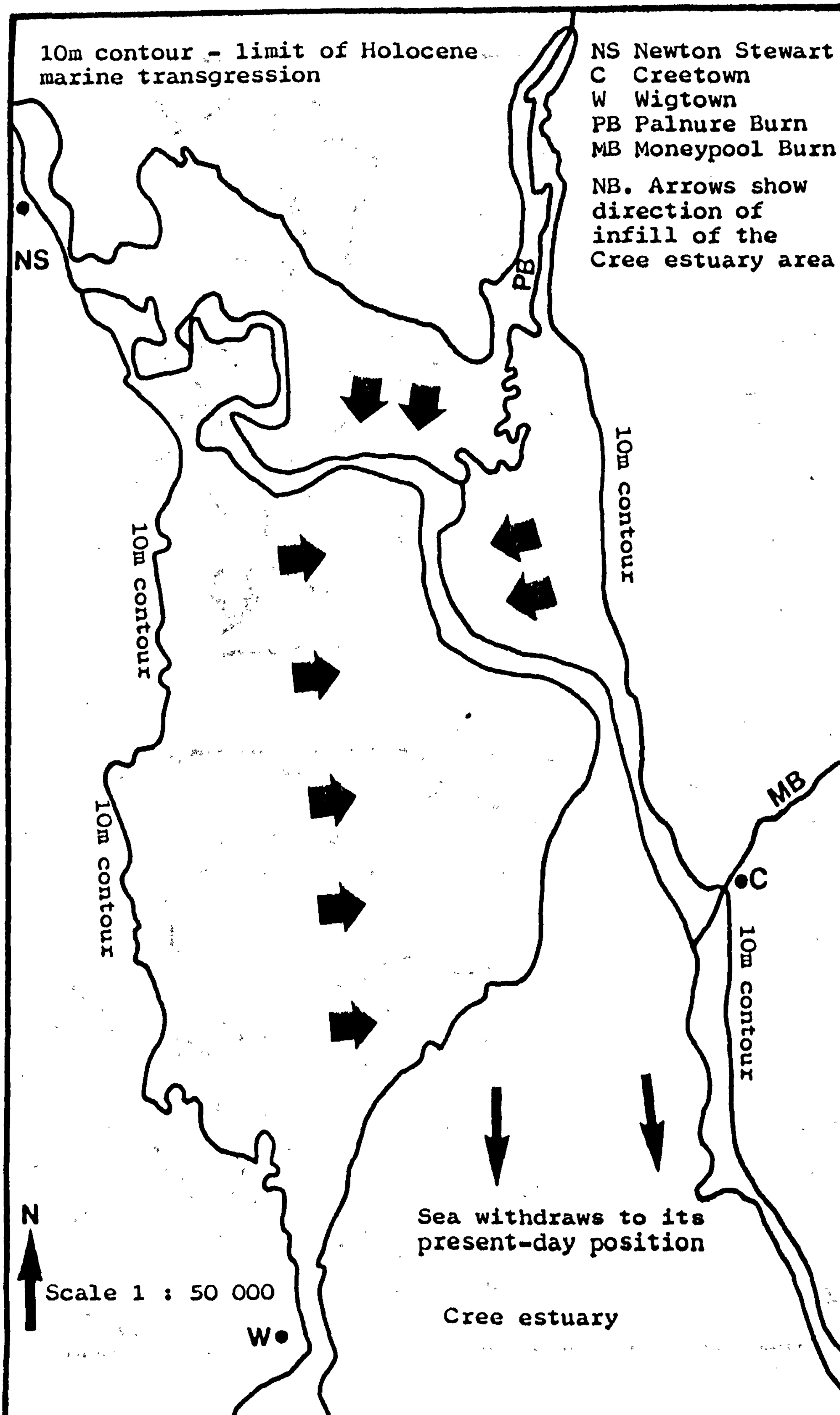


Fig.11.1 Direction of infilling of the Cree estuary area

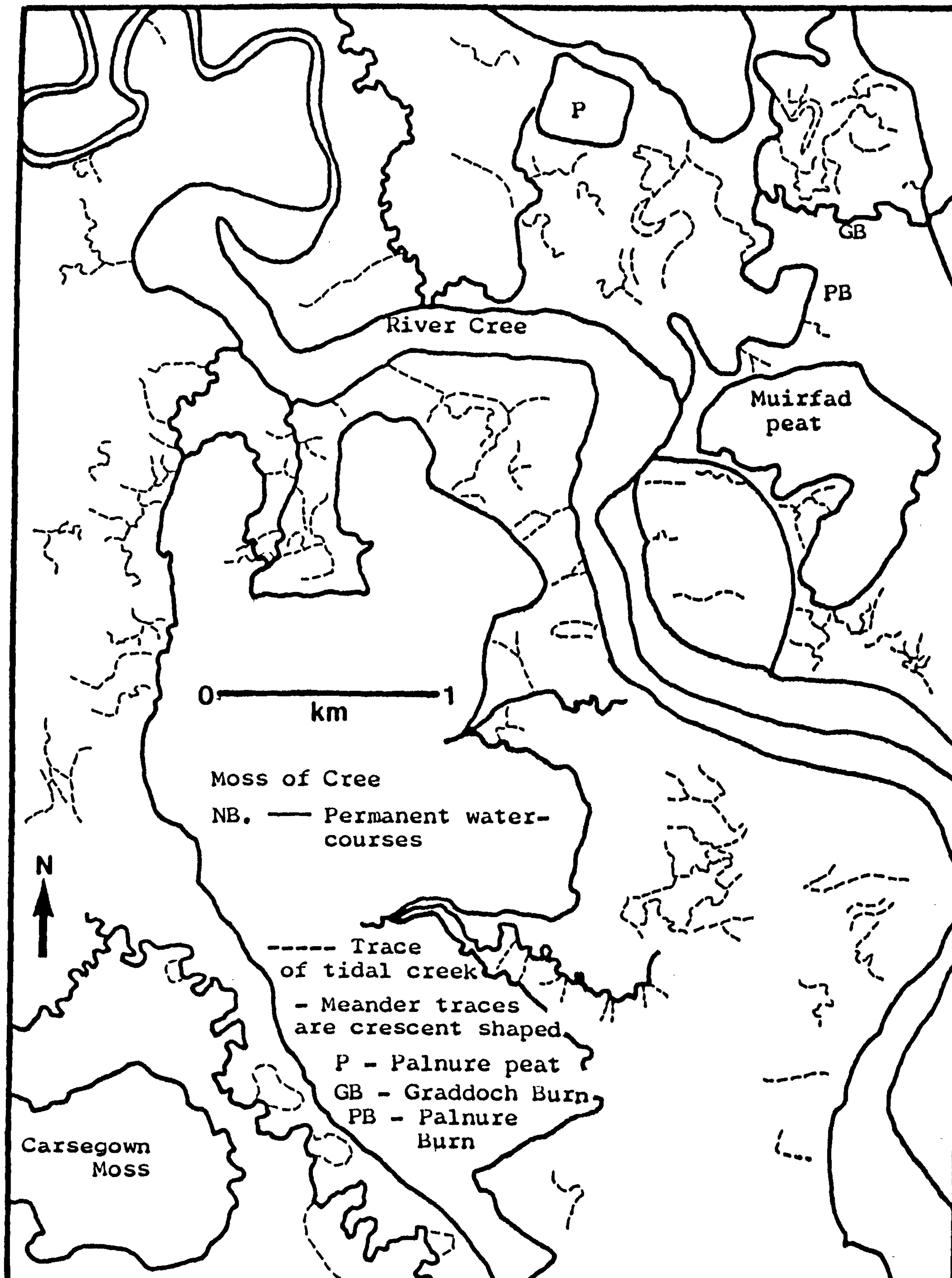


Fig.11.2 Pattern of "ancient" intertidal flat type dendritic drainage, upper Cree estuary area

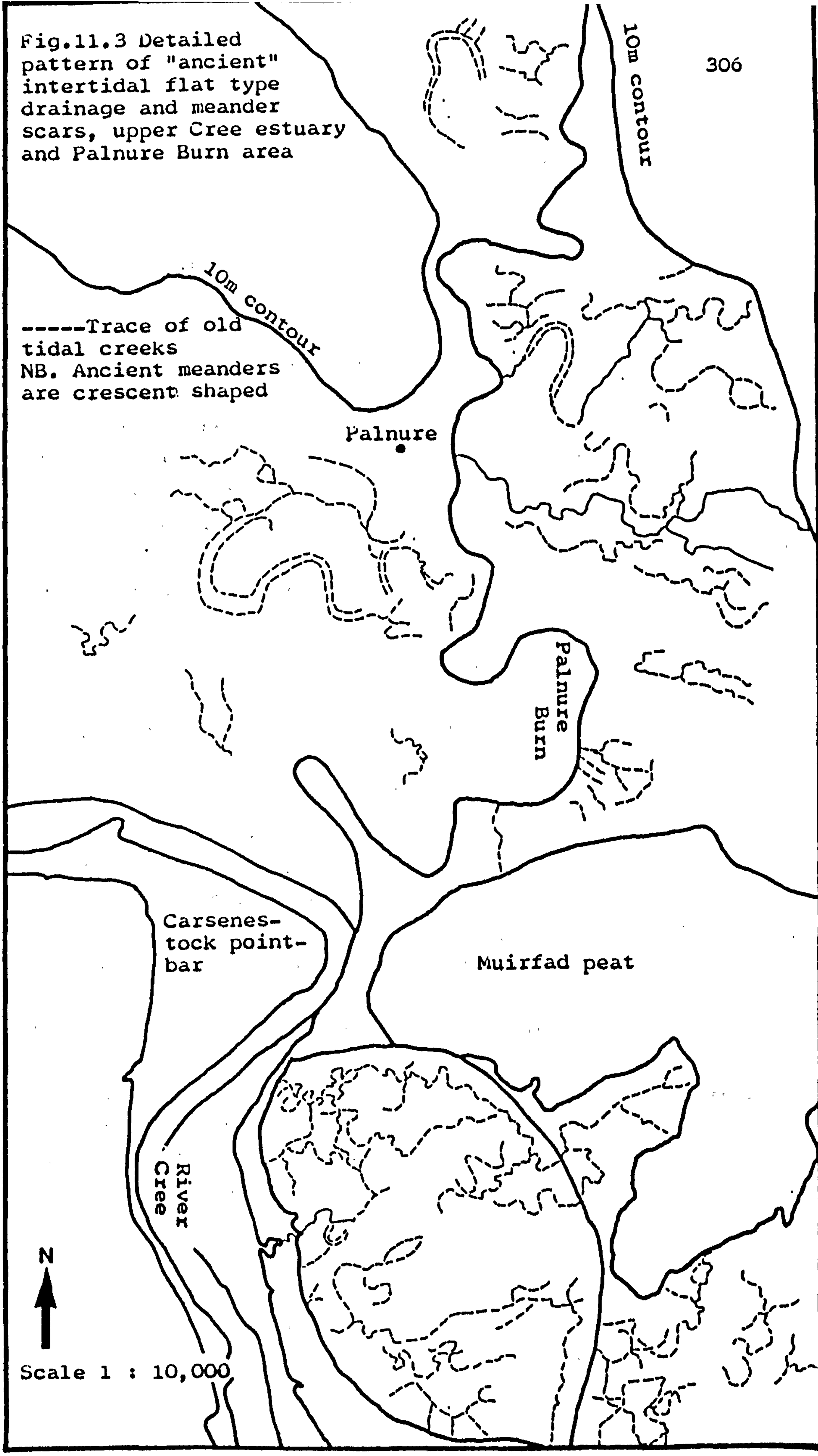


Fig.11.3 Detailed pattern of "ancient" intertidal flat type drainage and meander scars, upper Cree estuary and Palnure Burn area

superimposed upon the older marine/estuarine Holocene sequence (Fig. 11.4). Furthermore, due to incision, the present-day infill sequence is laterally juxtaposed with the deposits of earlier (older) Holocene environments.

The Cree estuary is 19km in length and, since c. 5,000 years B.P., approximately 7.5km of its length has been infilled and its cross-sectional area has been reduced to that of a river that meanders through a fluvially-incised tidal-flat sequence as far as Creetown. South of Creetown the cross-sectional area is already much reduced by extensive intertidal-flat deposition. Infilling is still continuing.

11.2 TO WHAT EXTENT HAVE THE PROBLEMS OUTLINED IN CHAPTER 3 BEEN SOLVED BY THE RESEARCH PROJECT ?

The phrase "the present is the key to the past" is much quoted in geology. However much it is used, it remains persistently true and has much significance as far as the work presented in this thesis is concerned.

However, there are limits to its application, these limits varying with individual cases. If the evidence (i.e. past and present sedimentary, stratigraphical, biological evidence) is partial or is not available, then no satisfactory conclusions can be reached.

The history of Holocene to present-day sedimentation of the Wigtown Bay area, including that of the head of the Cree estuary, is documented briefly in several papers by Jardine. The broad chronological sequence of events, development of environments and associated deposits is known. Comparison can be made with other regions of the Solway Firth. It appears, however, that when refinement of the range of environments is required the initial problems still remain. It is relatively easy from the sedimentary record to establish the range of deposits present but to pin-point the environments of deposition proves elusive. Other factors have to

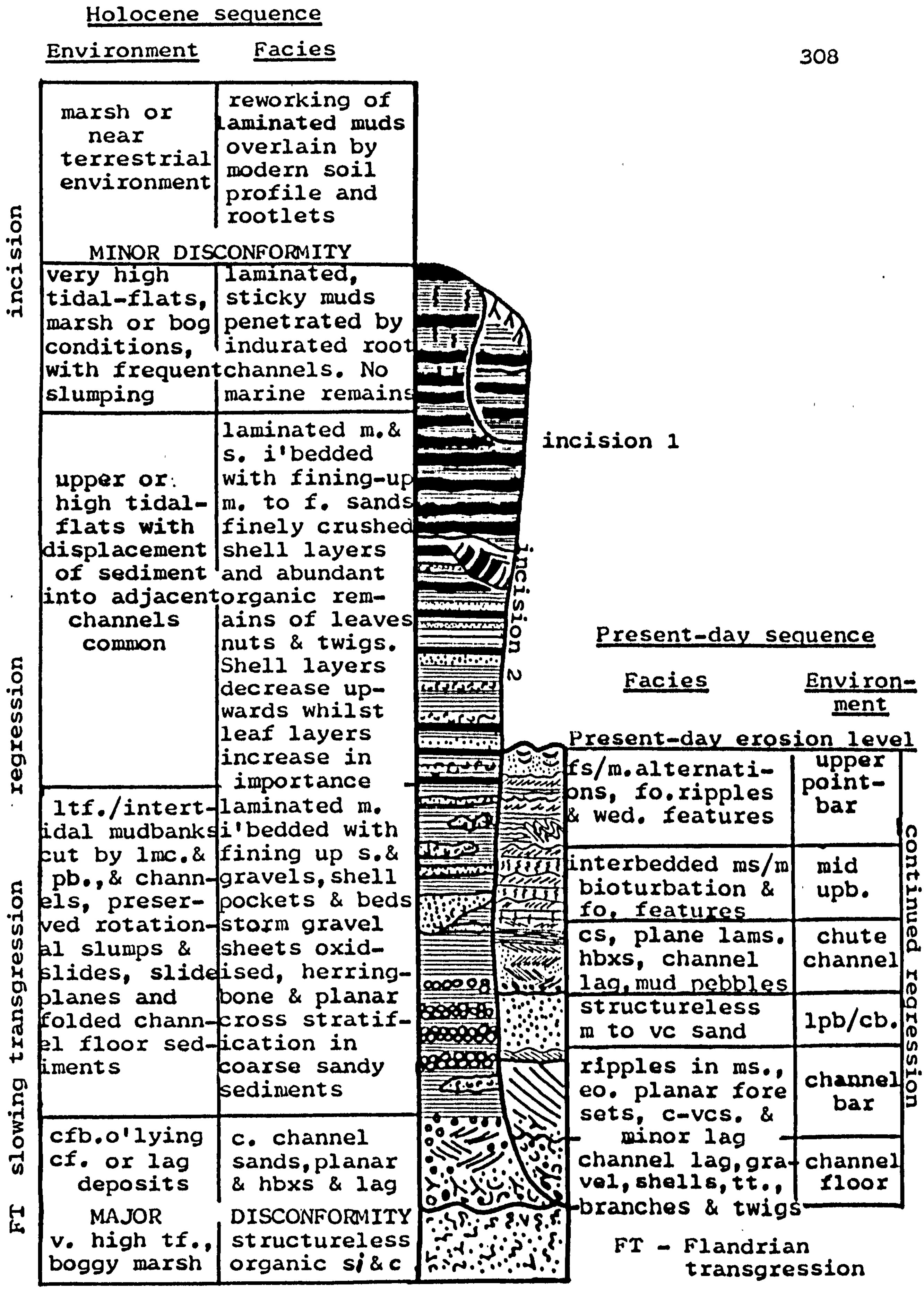


Fig.11.4 Vertical facies sequences and associated environments of Holocene to present-day environments at the head of the Cree estuary. Abbreviations as follows : ltf - lower tidal-flats,lmc-laterally migrating creeks, pb - point-bars, cfb - channel-floor bars, cf - channel floor, tf - tidal-flat, m - muds or medium, s - sands, f - fine, c - coarse or clays, si - silts, hbxs - herringbone cross stratification, fs/m - fine sand & mud, ms/m - medium sand & mud, eo & fo - ebb & flood oriented, wed - water ejection deformation features, cs - coarse sand, vc-very coarse, vcs - very coarse sand, tt - tree trunks, u & lpb - upper & lower point-bar, cb - channel bottom

be taken into consideration to solve this problem.

The root of the problem of determining the type of environment present lies in two factors: scale of environment and its preservation potential, the latter closely linked with the types of deposits and the energy of the environments. It appears that if a particular environment was extensive the smaller features were lost; only broad and vague features were preserved. The environments were on the whole dynamic, with active reworking of sediments. Small-scale features are not retained or, possibly, not formed because the Holocene sequence was chiefly muddy.

Comparison with the present-day deposits enables some further refinement. Comparison of broad features is possible, together with those of some smaller-scale features. The easiest comparison is made between channel-type deposits, clearly recognised in both the Holocene and present-day sequence. It is possible to establish to some extent the type of bar present in the Holocene sequence because these structures appear to have a high preservation potential when overlain by a thick, finer-grade infill. One recognises that they <u>are</u> bar features by comparing them with similar structures in the present-day River Cree; both the grade of deposit and the size of sedimentary structure formed are similar. Furthermore, it is deduced that they are channel-floor bar deposits in relation to the overlying fining-upwards channel infill material. There, however, the comparison ends. On a smaller scale, the lack of sedimentary structures can be explained in terms of:

(a) Sediment composition - Most of the sediment available for deposition is very fine-grained mud and silt, in which structures rarely form.

(b) Processes - It is assumed that processes were similar throughout the Holocene epoch, <u>i.e.</u> they are/were two-fold. Suspension processes dominated over the high intertidal flats, river flanks and upper point-bars, whilst bedload processes dominate(d) in the channel. Where both processes operate(d), it is easier to distinguish between bedload and suspension processes in the Holocene sequence than in the present-day sequence. Therefore, sedimentary structures, typical of the transition zone in which both the above processes operated, did not form in Holocene times. Flaser and lenticular bedding are rarely preserved in the Holocene sequence.

It may be that the above-mentioned structures did form but were not preserved, or that there was indeed a sharp distinction between bedload and suspension conditions during the Holocene epoch. This implies that suspension processes were operating on extensive intertidal mud banks and bedload processes were confined to tidal gullies in an area that is presently an incised alluvial plain, thereby providing evidence of changing environments. The patchy distribution of a bedload/suspension mixture of structures of the Holocene sequence can be explained in terms of processes and sediment composition. The structures only form where an adequate balance of sand and mud is present - which was not available in Holocene times, either because it was not there or as a result of the polarisation of suspension and bedload processes within the environments. At present the suspension/bedload mixture of structures is found abundantly in the vicinity of Creetown and Moneypool Burn and on the large scale point-bars of the River Cree, e.g. at Carsenestock (see box-core studies, Chapter 10). It appears that there is more sand in the upper Cree estuary at present than in the past.

In conclusion, it can be said that, however hard one tries, it is possible to establish and refine environments only to a certain extent but, unfortunately, no further.

11.3 RECOMMENDATIONS FOR FURTHER RESEARCH

No further elucidation of the "types" of environments at the head of the Cree estuary and Wigtown Bay area is likely to be possible. It is assumed that the full range of environments and sub-environments of the Holocene has been established. However, it is suggested that details of these environments may be further refined in the following manner:

Fresh research should be directed towards and concentrate upon the chronology of events. For example, can details of timing of the marine transgression be improved? There appears to be plenty of potential for dating of wood and shell fragments at key locations and levels within the sedimentary and stratigraphic sequence of the area. Further refinement of the nature of the environments and the chronology of events possibly could be achieved by botanical studies. The definite need to pinpoint the timing of events more accurately remains. The correlation of onshore and offshore (B.G.S.) sedimentary and stratigraphical sequences would allow an insight into the glacial to post-glacial history of the Wigtown Bay area and would establish more accurately the nature of marine transgression and regression.

It is considered that whichever path future research takes, the study will require to be multidisciplinary to obtain satisfactory results.

A myriad of questions arose as the research project progressed. It is the writer's hope that this thesis will partly answer some of these questions, although many still remain.

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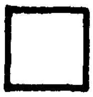
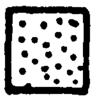
APPENDIX 1

Symbols for lithology, sedimentary structures and organic features

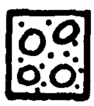
Lithology


Pale grey clay


Dark grey-blue clay


Sands


Pebble supported gravels


Matrix supported gravels


Clay nodules (Not oxidised)

Sharp, irregular bed contact

Sharp, planar bed contact

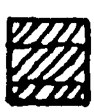
Gradational bed contact

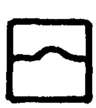
Sedimentary Structures


Flaser bedding


Lenticular bedding


Herringbone cross-stratification


Planar cross-strat-ification


Symmetrical ripples


Asymmetrical ripples


Oxidised clay 'hard-pan'


Convolute bedding


Mottling


Clay nodules with oxidised rim

Organic Features


Wavy, organic/clay laminations


Leaf bands


Ancient root channels/ remains


Modern root remains


Shell beds/bands/pockets


Twig remains


Branch/tree-trunk remains

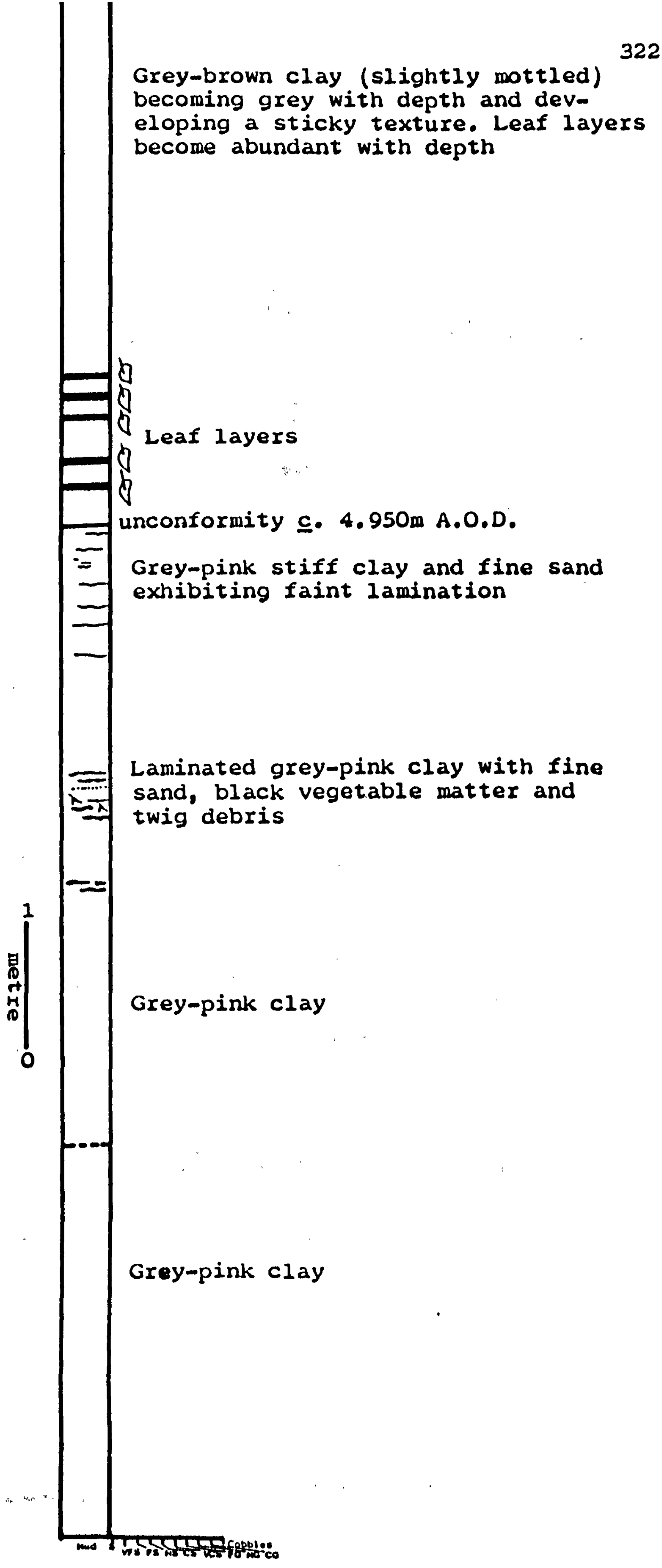

Carbonaceous streaks


Carbonaceous pods

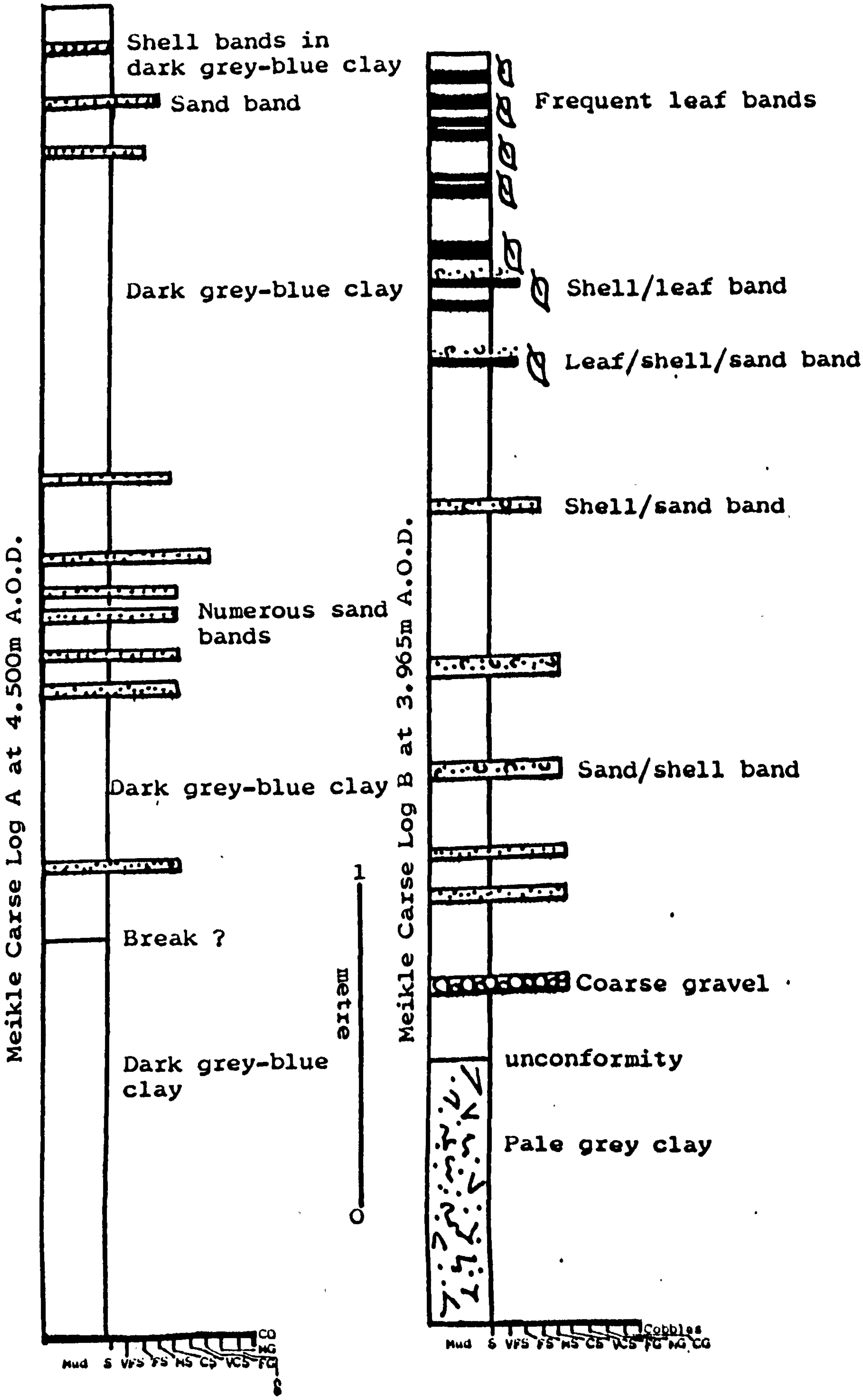
Grain-size Abbreviations

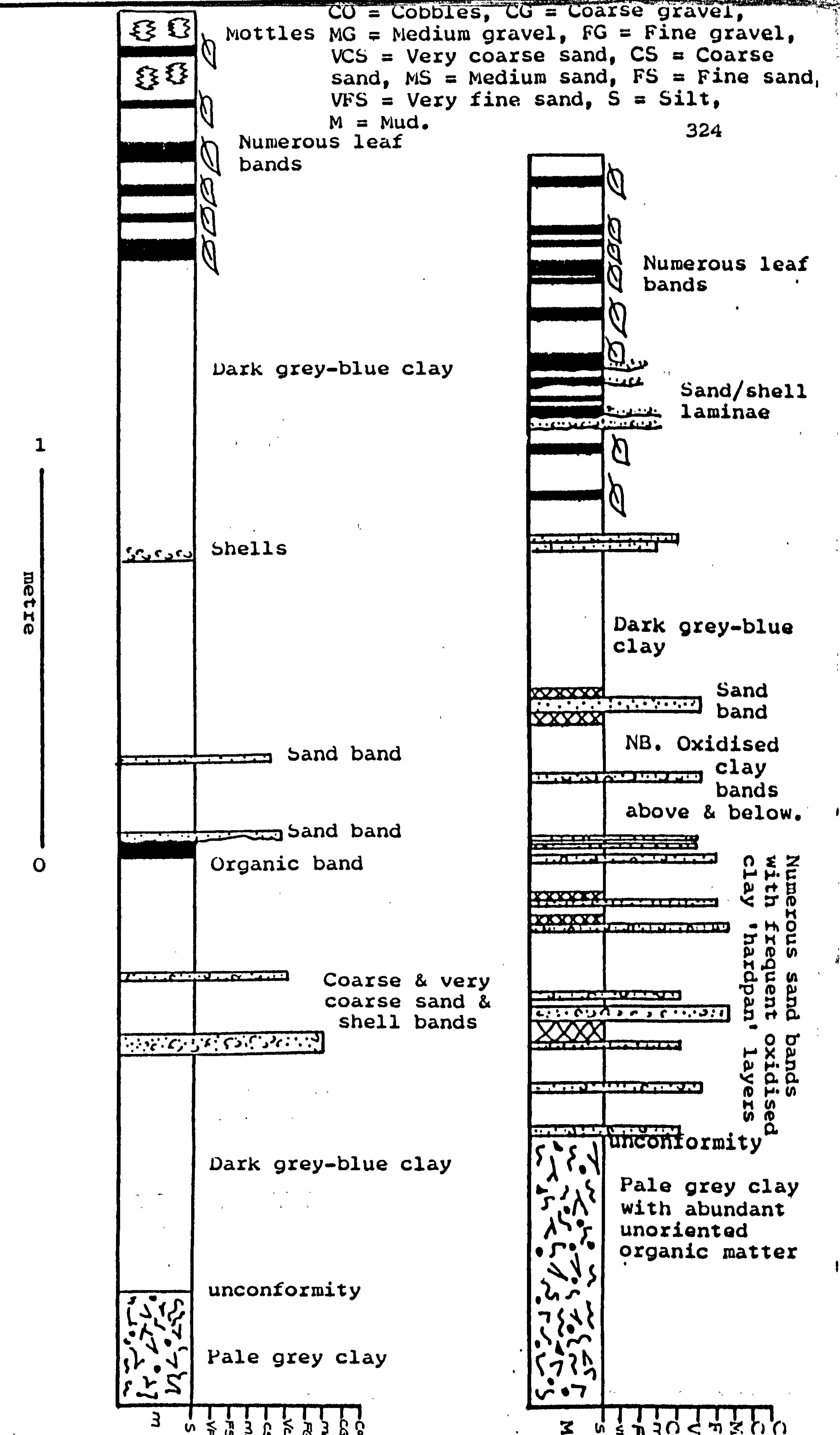
CO = Cobbles, CG = Coarse gravel, MG = Medium gravel, FG = Fine gravel, VCS = Very coarse sand, CS = Coarse sand, MS = Medium sand, FS = Fine sand, VFS = Very fine sand, S = Silt, M = Mud

The altitudes recorded in all the pages of Appendix 1 are the altitudes of the tops of the sections or bore logs.



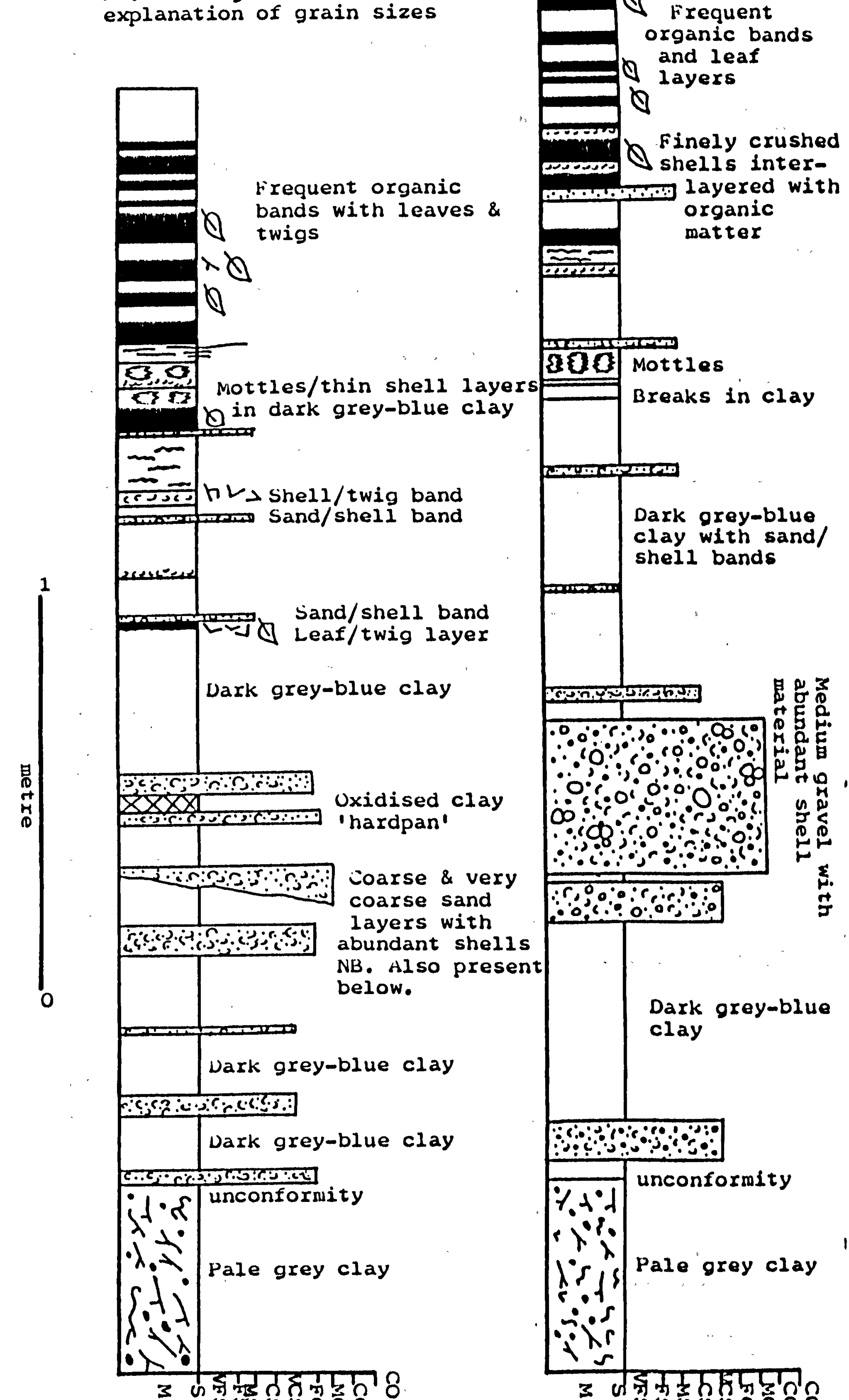
Parkmaclurg Borehole, River Cree at 9.200m A.O.D.


Meikle Carse Log A at 4.500m A.O.D.
Shell bands in dark grey-blue clay
Sand band
Dark grey-blue clay
Numerous sand bands
Dark grey-blue clay
Break ?
Dark grey-blue clay
metre
1
0
Mud S VFS FS MS CS VCS FG MG CG
Meikle Carse Log B at 3.965m A.O.D.
Frequent leaf bands
Shell/leaf band
Leaf/shell/sand band
Shell/sand band
Sand/shell band
Coarse gravel
unconformity
Pale grey clay
Mud S VFS FS MS CS VCS FG MG CG Cobbles

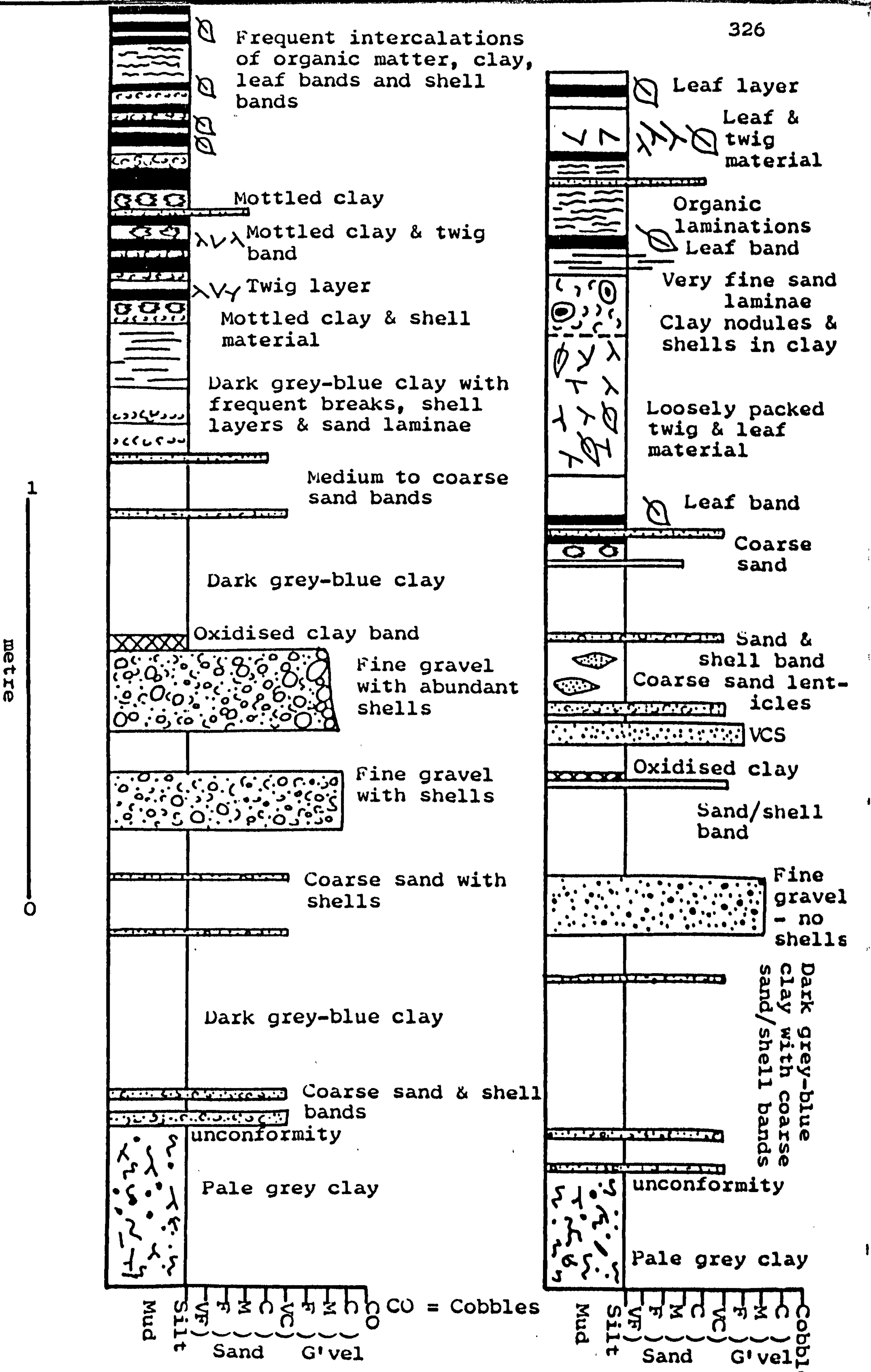


Meikle Carse Log C at 4.185m A.O.D.

Meikle Carse Log D at 4.310m A.O.D.

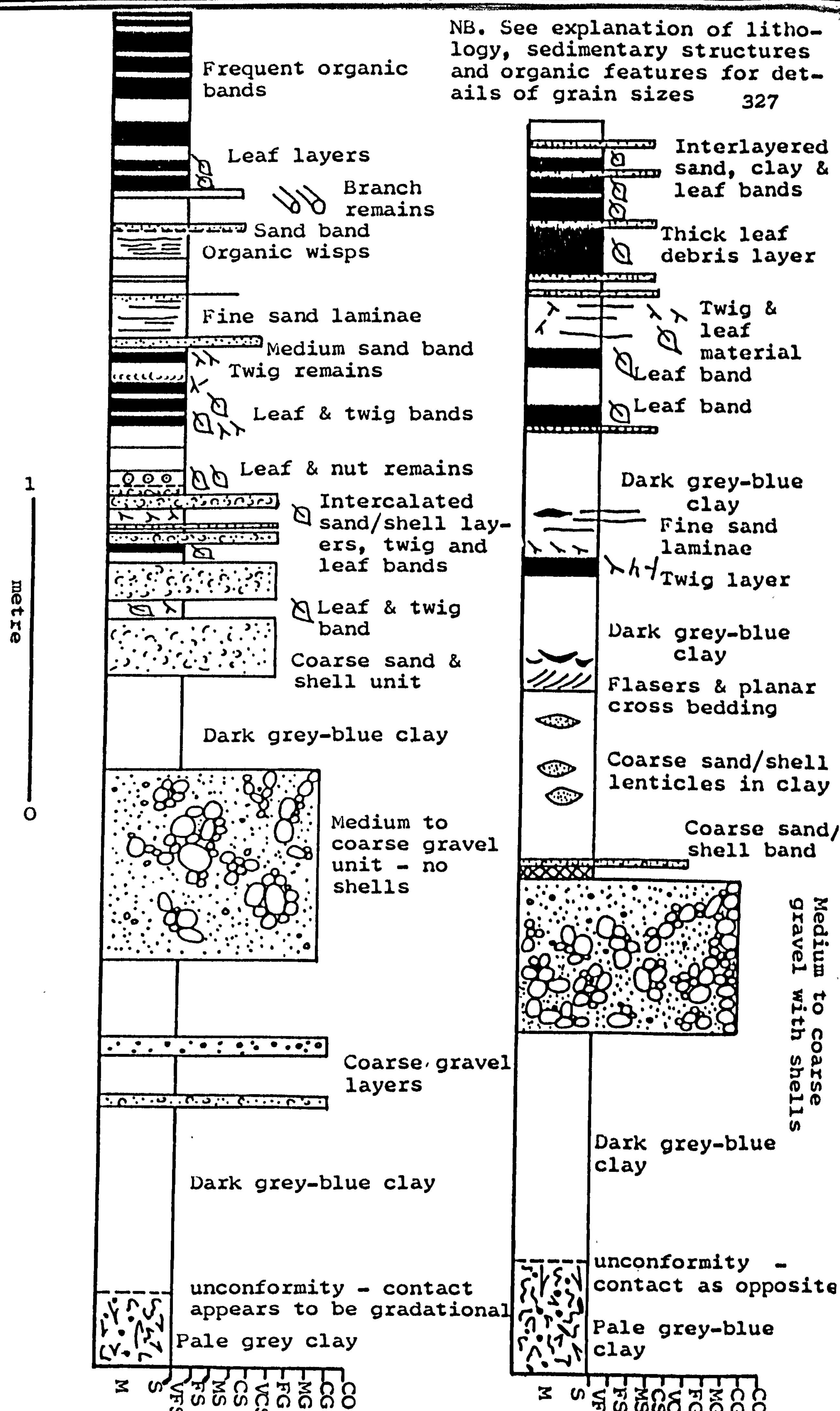


Meikle Carse Log E at 4.270m A.O.D. Meikle Carse Log F at 4.190m A.O.D.



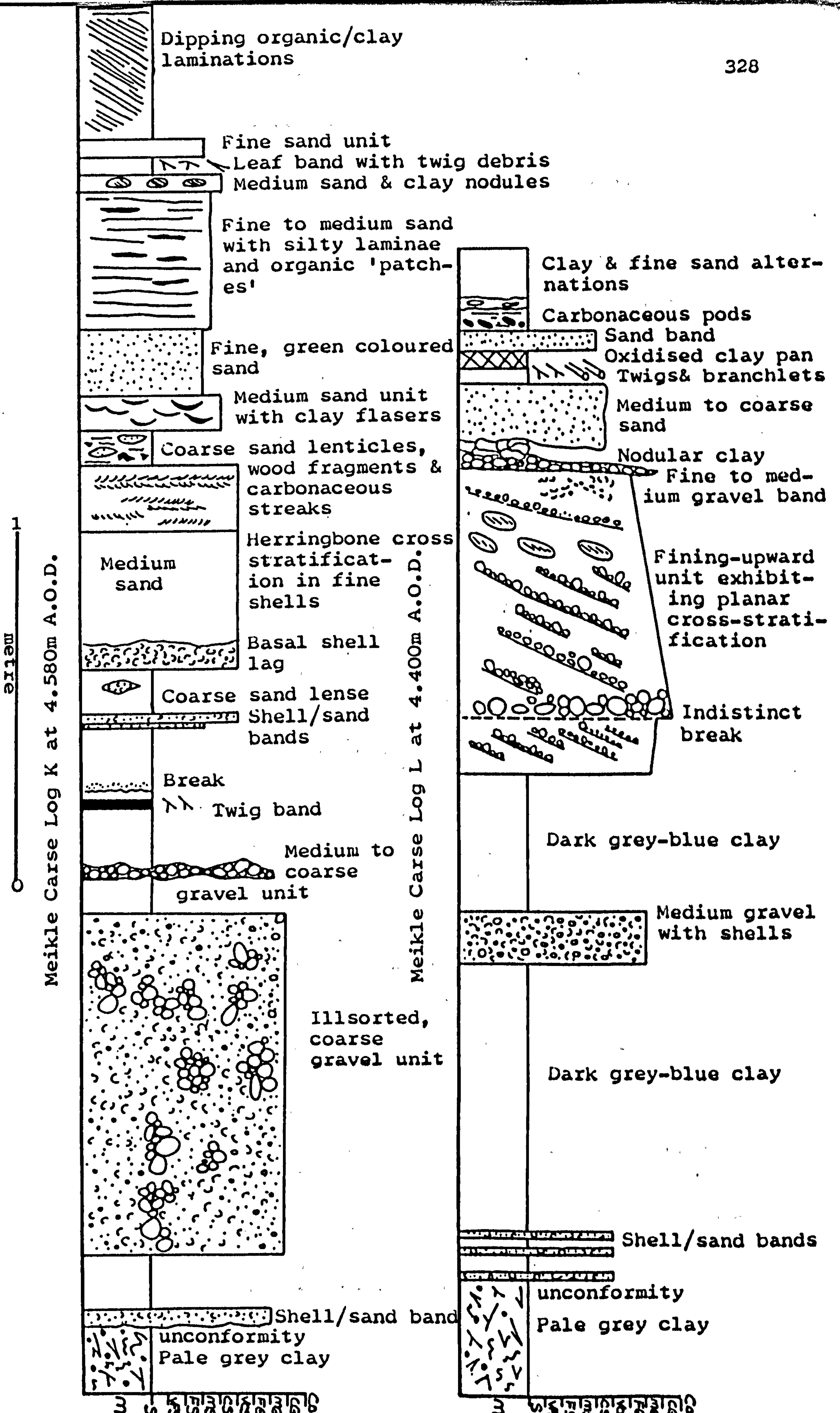
Meikle Carse Log G at 4.100m A.O.D.

Meikle Carse Log H at 4.065m A.O.D.

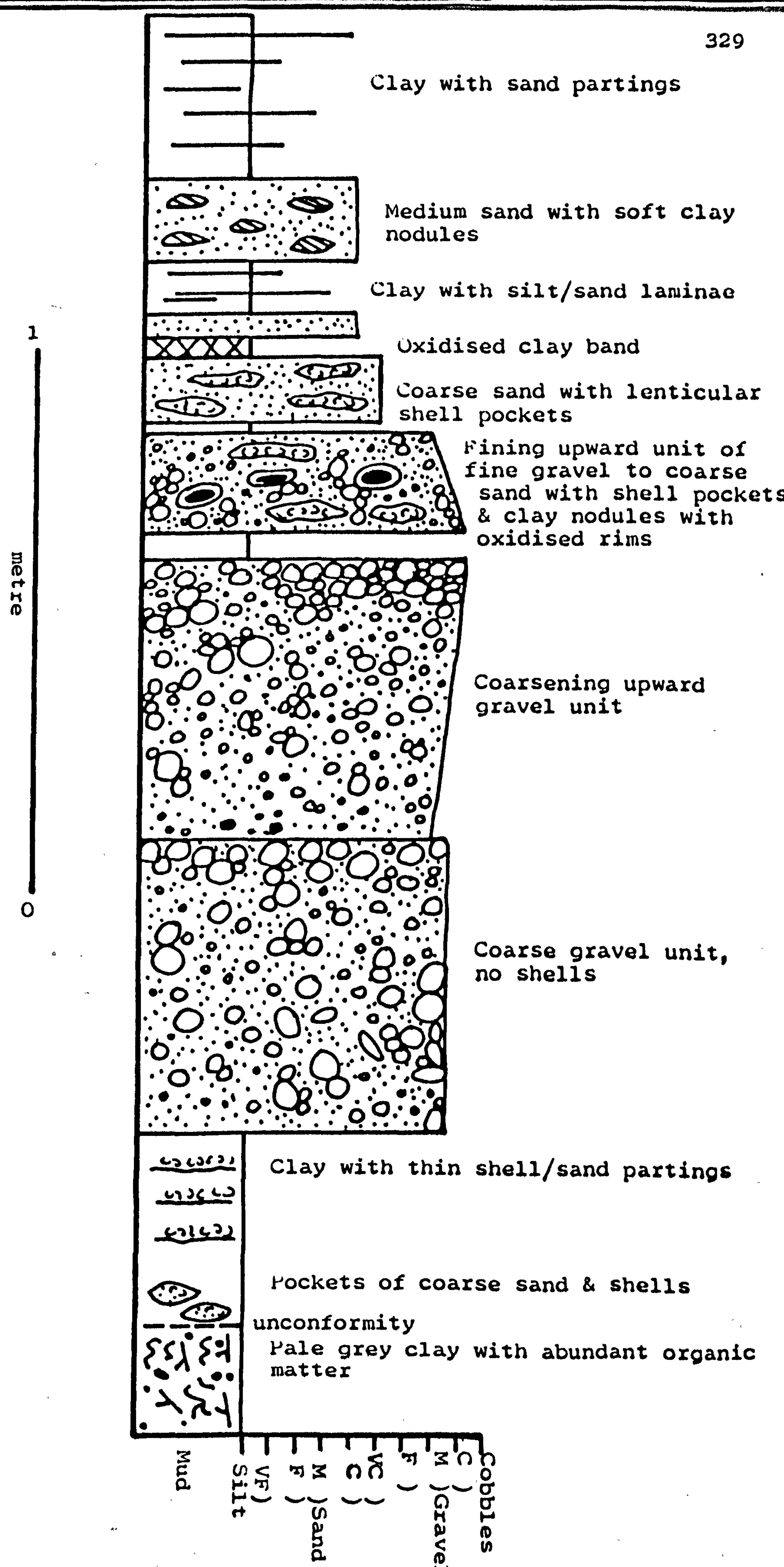


Meikle Carse Log I at 4.600m A.O.D.

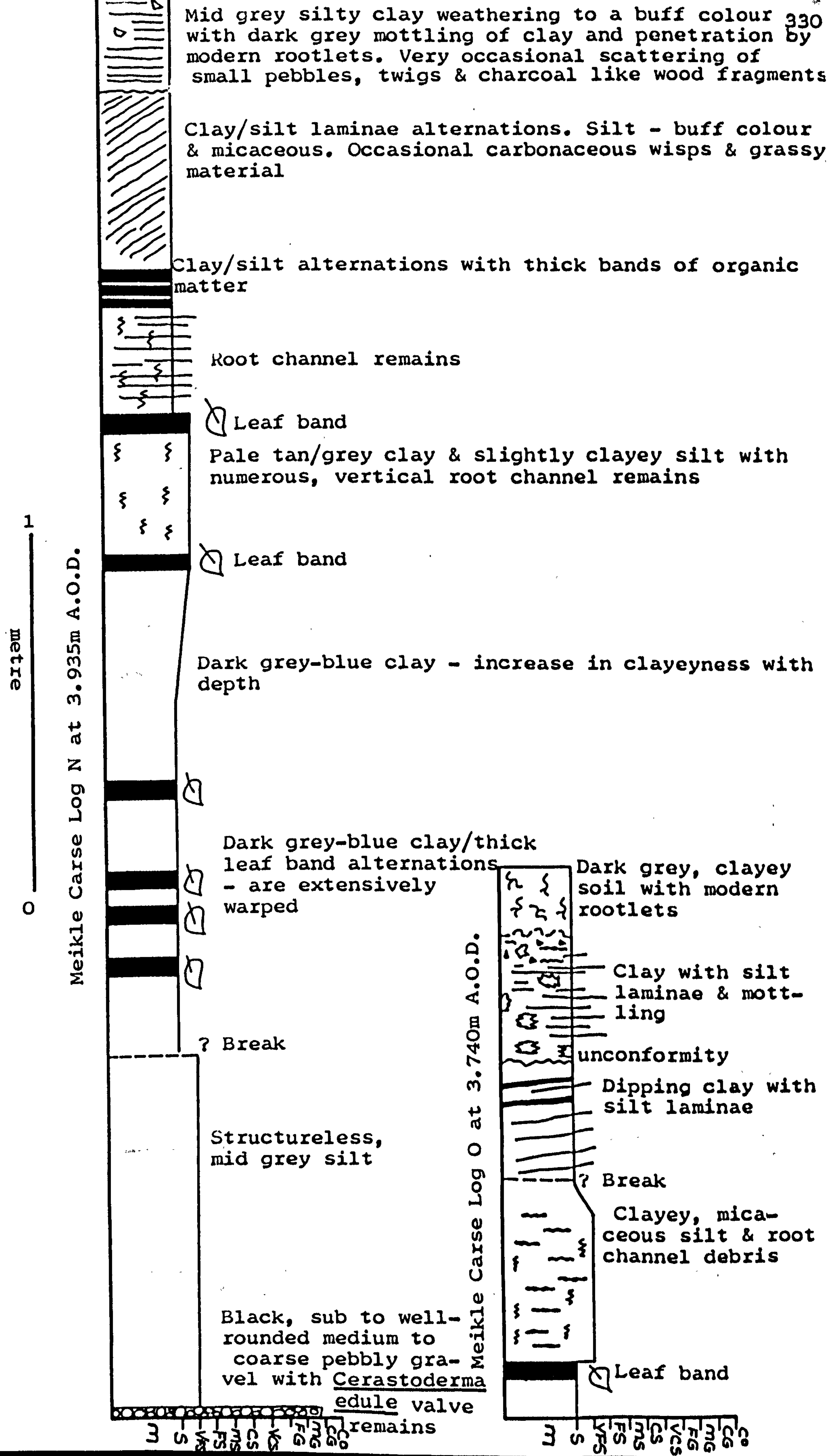
Meikle Carse Log J at 4.580m A.O.D.



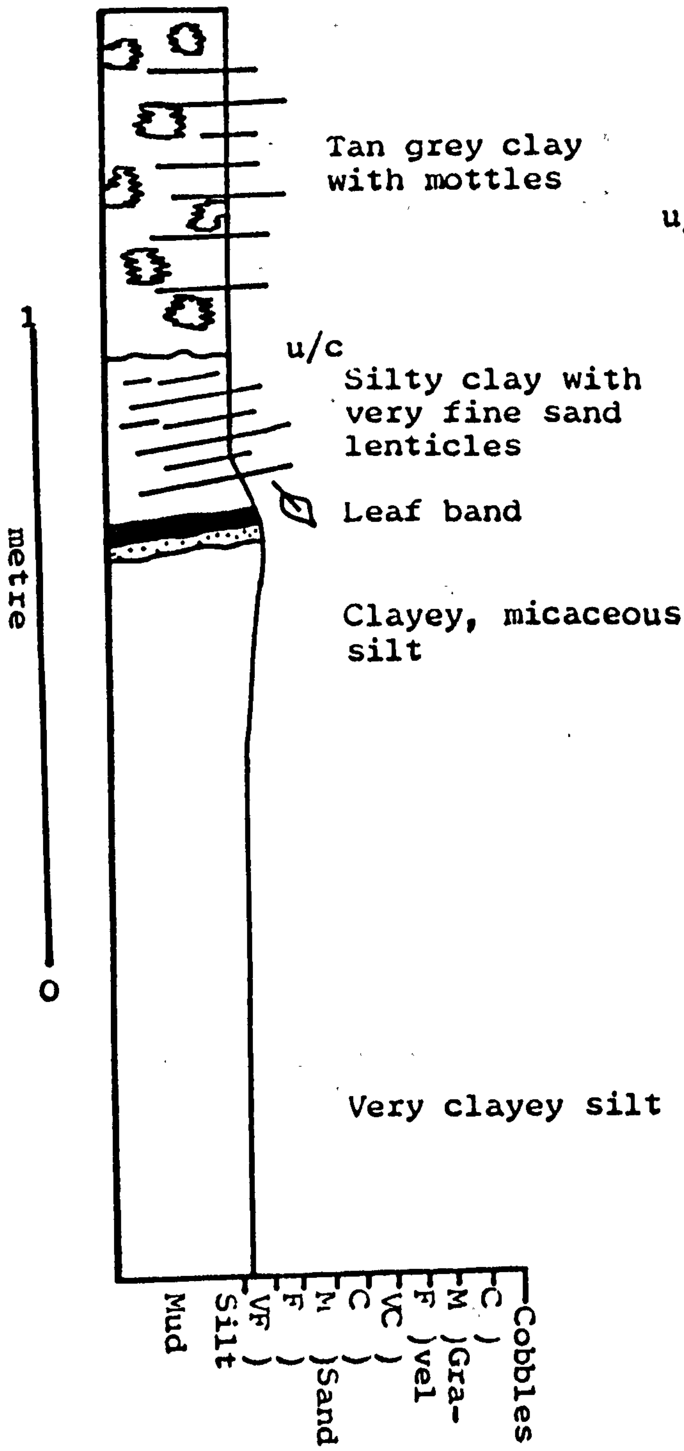
Dipping organic/clay laminations
Fine sand unit
Leaf band with twig debris
Medium sand & clay nodules
Fine to medium sand with silty laminae and organic 'patches'
Fine, green coloured sand
Medium sand unit with clay flasers
Coarse sand lenticles, wood fragments & carbonaceous streaks
Herringbone cross stratification in fine shells
Medium sand
Basal shell lag
Coarse sand lense
Shell/sand bands
Break
Twig band
Medium to coarse gravel unit
Illsorted, coarse gravel unit
Shell/sand band
unconformity
Pale grey clay
metre
1
0
Meikle Carse Log K at 4.580m A.O.D.
Meikle Carse Log L at 4.400m A.O.D.
Clay & fine sand alternations
Carbonaceous pods
Sand band
Oxidised clay pan
Twigs& branchlets
Medium to coarse sand
Nodular clay
Fine to medium gravel band
Fining-upward unit exhibiting planar cross-stratification
Indistinct break
Dark grey-blue clay
Medium gravel with shells
Dark grey-blue clay
Shell/sand bands
unconformity
Pale grey clay



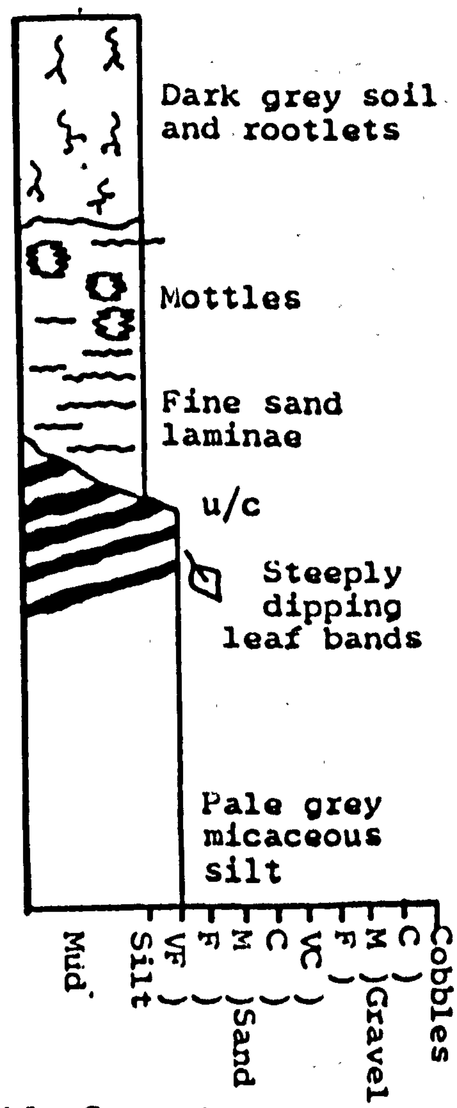
Meikle Carse Log M at 4.180m A.O.D.


Mid grey silty clay weathering to a buff colour with dark grey mottling of clay and penetration by modern rootlets. Very occasional scattering of small pebbles, twigs & charcoal like wood fragments
Clay/silt laminae alternations. Silt - buff colour & micaceous. Occasional carbonaceous wisps & grassy material
Clay/silt alternations with thick bands of organic matter
Root channel remains
Leaf band
Pale tan/grey clay & slightly clayey silt with numerous, vertical root channel remains
Leaf band
Dark grey-blue clay - increase in clayeyness with depth
Dark grey-blue clay/thick leaf band alternations - are extensively warped
? Break
Structureless, mid grey silt
Black, sub to well-rounded medium to coarse pebbly gravel with Cerastoderma edule valve remains
1
metre
0
Meikle Carse Log N at 3.935m A.O.D.
Meikle Carse Log O at 3.740m A.O.D.
Dark grey, clayey soil with modern rootlets
Clay with silt laminae & mottling
unconformity
Dipping clay with silt laminae
? Break
Clayey, micaceous silt & root channel debris
Leaf band
m S VFS FS mS CS VCS FG mG CG Co
m S VFS FS mS CS VCS FG mG CG Co

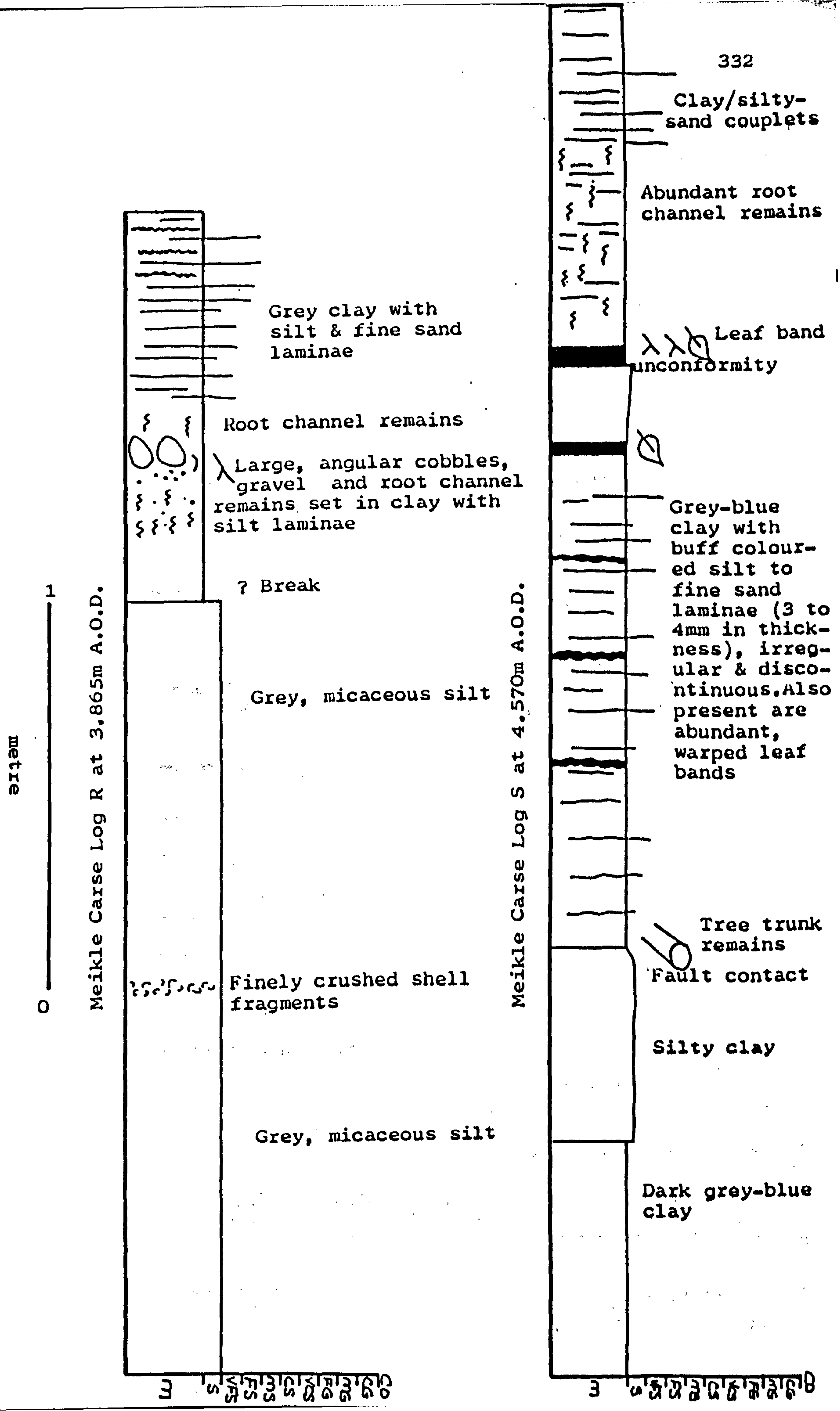
u/c = unconformity

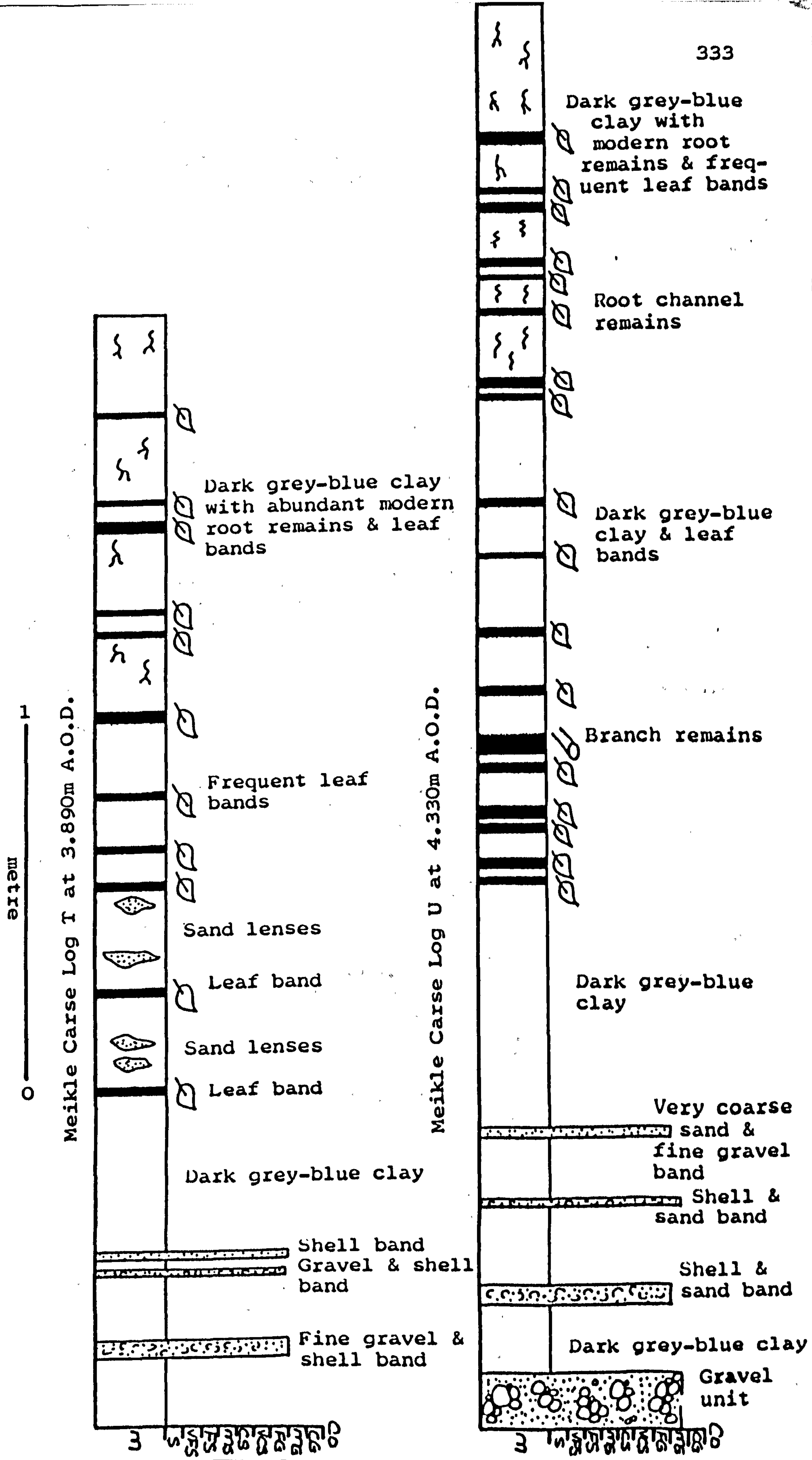


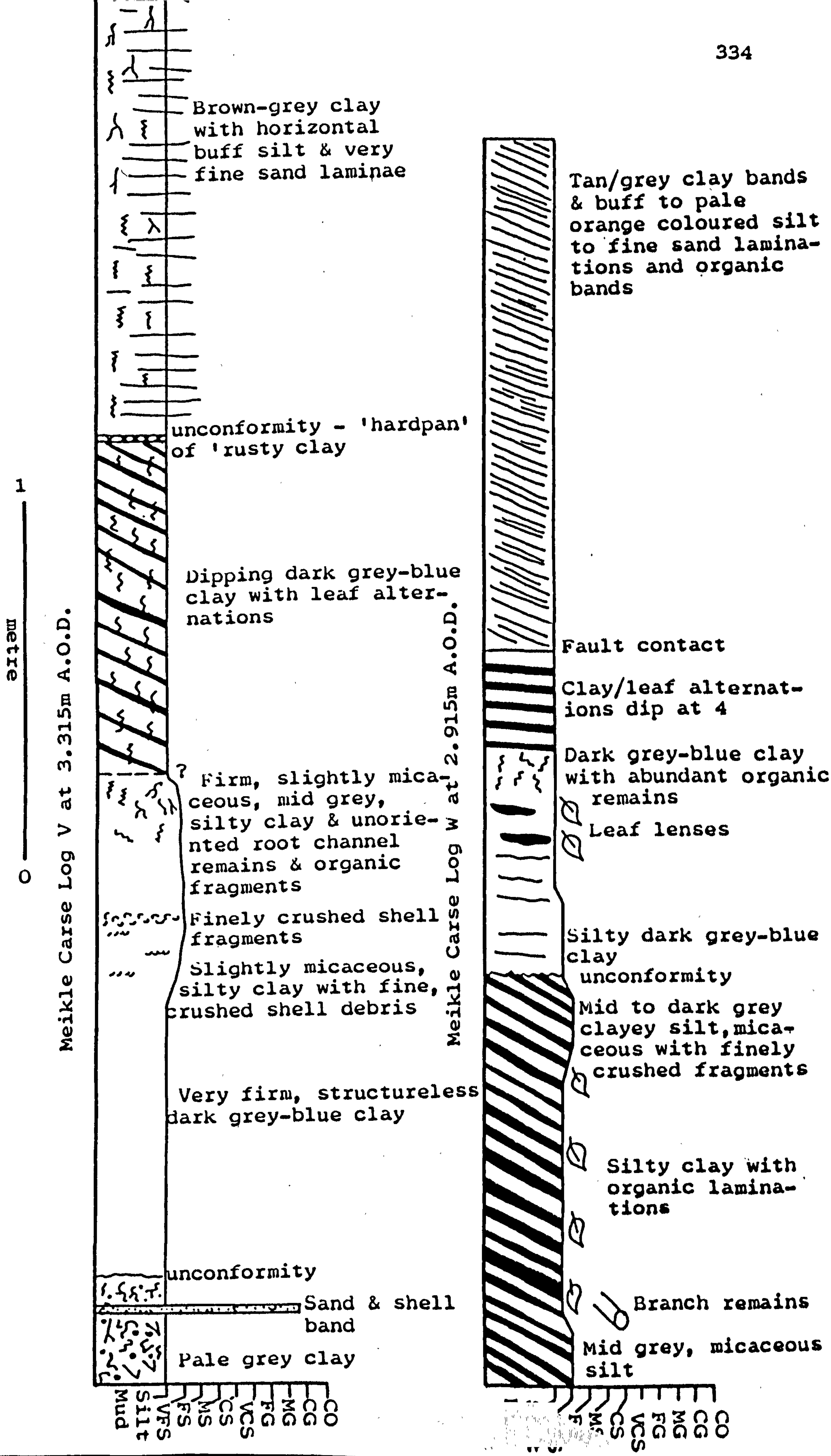
Meikle Carse Log P at
3,880m A.O.D.

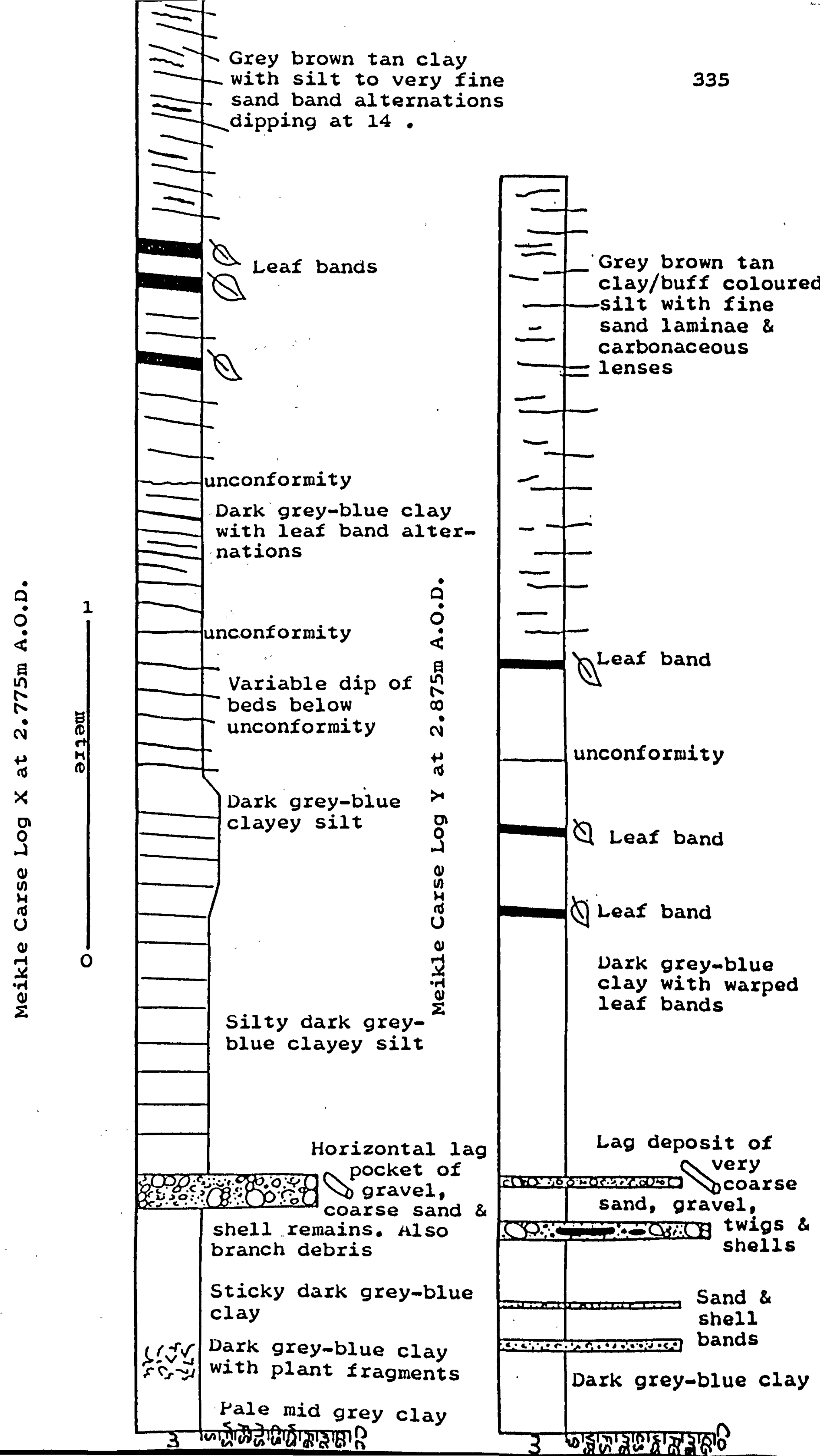


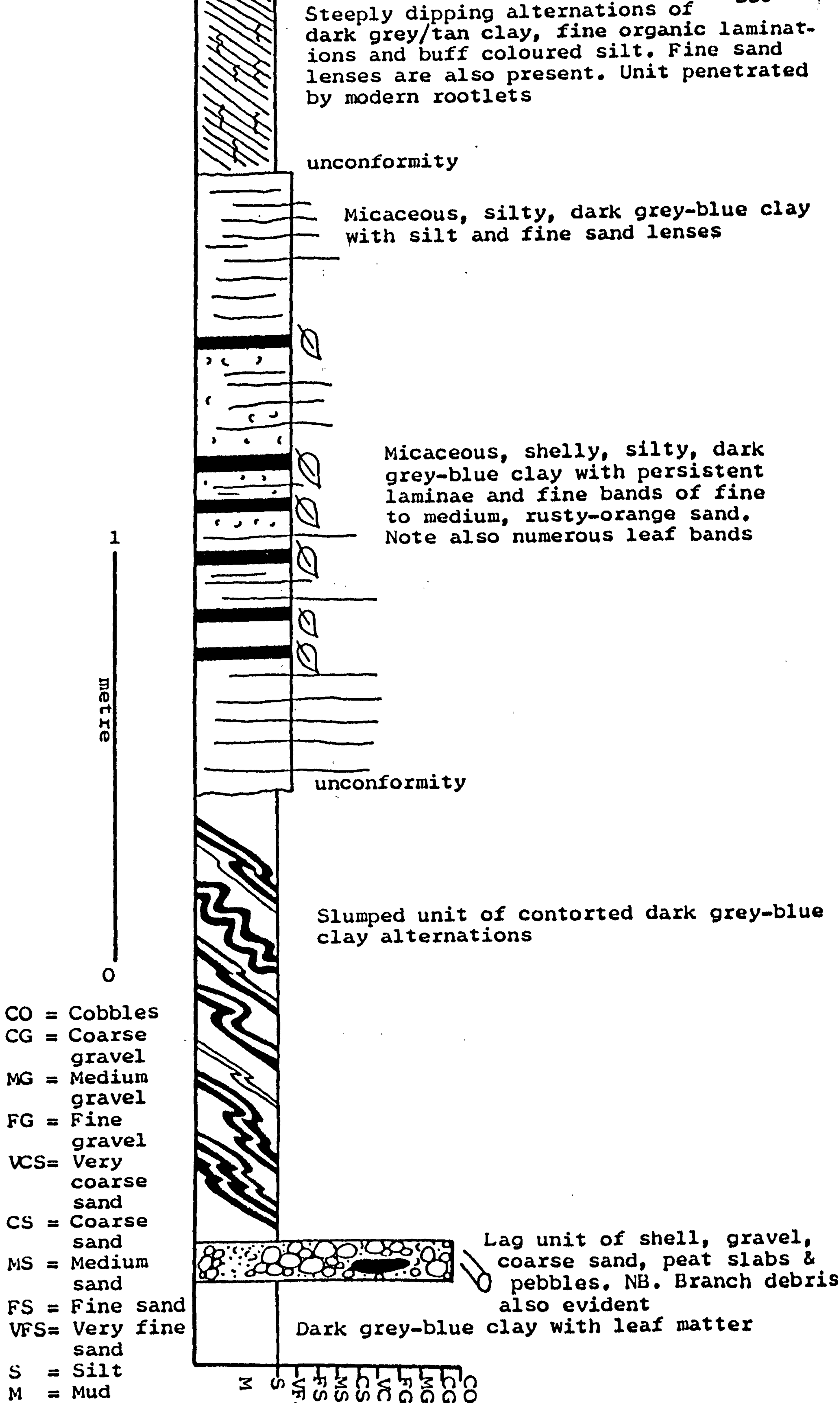
Meikle Carse Log Q at
3.895m A.O.D.


Meikle Carse Log R at 3.865m A.O.D.
metre
1
0
Grey clay with silt & fine sand laminae
Root channel remains
Large, angular cobbles, gravel and root channel remains set in clay with silt laminae
? Break
Grey, micaceous silt
Finely crushed shell fragments
Grey, micaceous silt
Meikle Carse Log S at 4.570m A.O.D.
Clay/silty-sand couplets
Abundant root channel remains
Leaf band
unconformity
Grey-blue clay with buff coloured silt to fine sand laminae (3 to 4mm in thickness), irregular & discontinuous.Also present are abundant, warped leaf bands
Tree trunk remains
Fault contact
Silty clay
Dark grey-blue clay

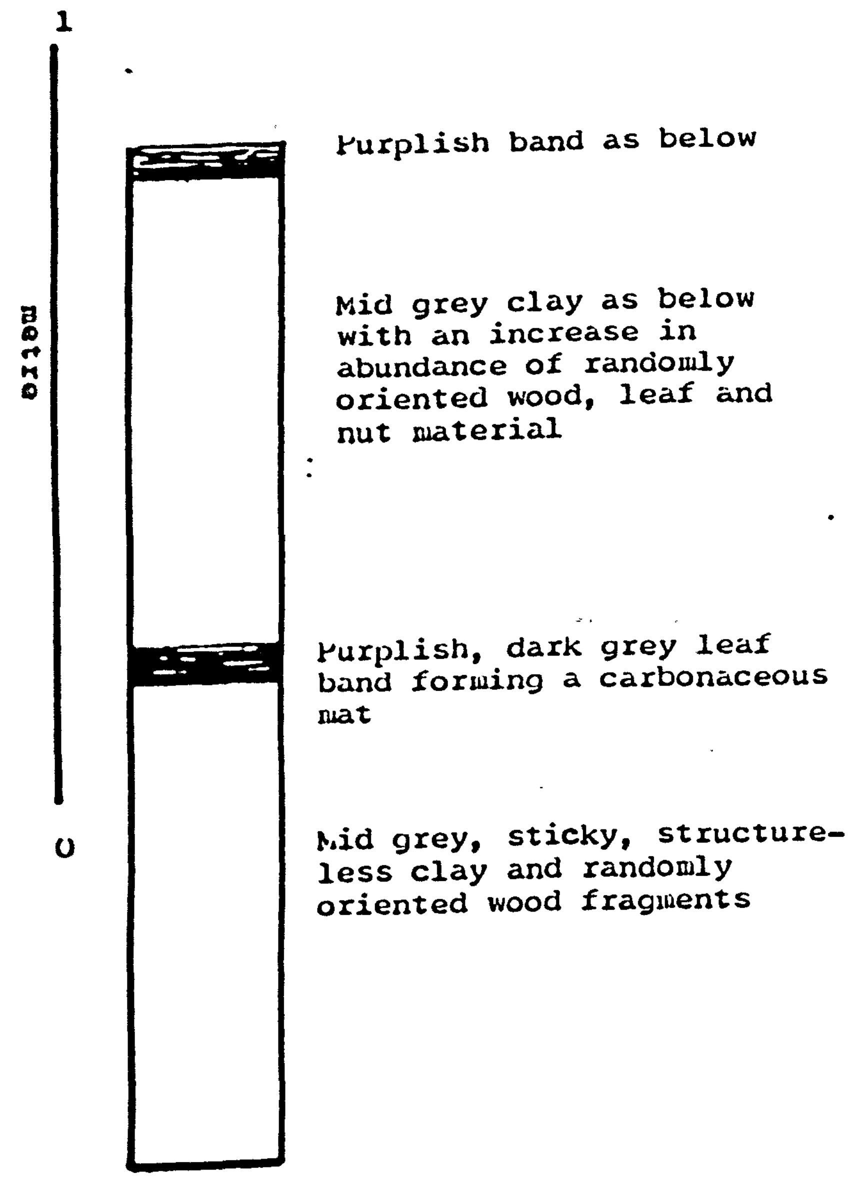

Meikle Carse Log T at 3.890m A.O.D.
1
metre
0
Dark grey-blue clay with abundant modern root remains & leaf bands
Frequent leaf bands
Sand lenses
Leaf band
Sand lenses
Leaf band
Dark grey-blue clay
Shell band
Gravel & shell band
Fine gravel & shell band
Meikle Carse Log U at 4.330m A.O.D.
Dark grey-blue clay with modern root remains & frequent leaf bands
Root channel remains
Dark grey-blue clay & leaf bands
Branch remains
Dark grey-blue clay
Very coarse sand & fine gravel band
Shell & sand band
Shell & sand band
Dark grey-blue clay
Gravel unit


Brown-grey clay with horizontal buff silt & very fine sand laminae
unconformity - 'hardpan' of 'rusty clay
Dipping dark grey-blue clay with leaf alternations
? Firm, slightly micaceous, mid grey, silty clay & unoriented root channel remains & organic fragments
Finely crushed shell fragments
Slightly micaceous, silty clay with fine, crushed shell debris
Very firm, structureless dark grey-blue clay
unconformity
Sand & shell band
Pale grey clay
Mud Silt VFS FS MS CS VCS FG MG CG CO
1
0
metre
Meikle Carse Log V at 3.315m A.O.D.
Meikle Carse Log W at 2.915m A.O.D.
Tan/grey clay bands & buff to pale orange coloured silt to fine sand laminations and organic bands
Fault contact
Clay/leaf alternations dip at 4
Dark grey-blue clay with abundant organic remains
Leaf lenses
Silty dark grey-blue clay
unconformity
Mid to dark grey clayey silt, micaceous with finely crushed fragments
Silty clay with organic laminations
Branch remains
Mid grey, micaceous silt
FS MS CS VCS FG MG CG CO

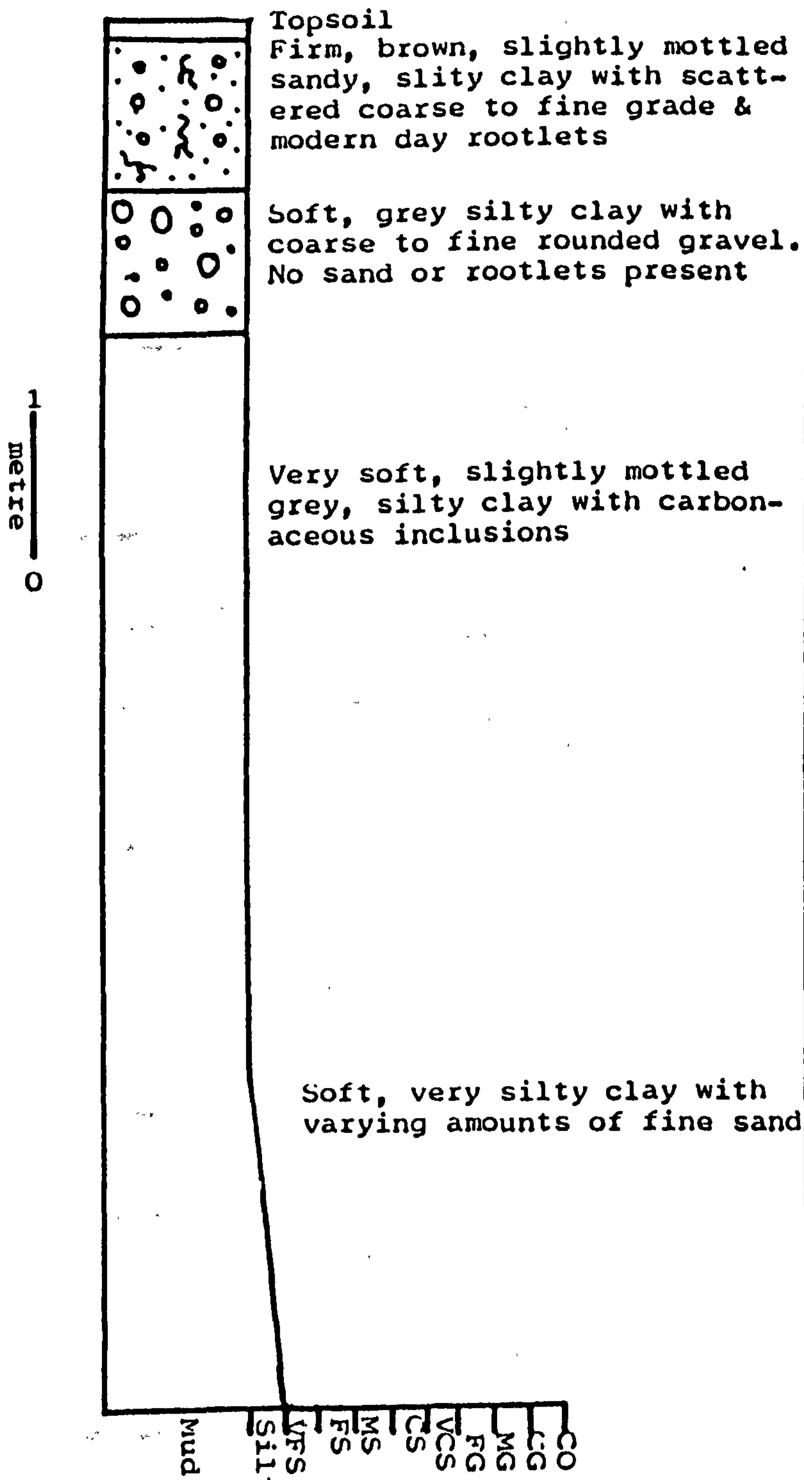

Meikle Carse Log X at 2.775m A.O.D.
1
metre
0
Grey brown tan clay with silt to very fine sand band alternations dipping at 14 .
Leaf bands
unconformity
Dark grey-blue clay with leaf band alternations
unconformity
Variable dip of beds below unconformity
Dark grey-blue clayey silt
Silty dark grey-blue clayey silt
Horizontal lag pocket of gravel, coarse sand & shell remains. Also branch debris
Sticky dark grey-blue clay
Dark grey-blue clay with plant fragments
Pale mid grey clay
Meikle Carse Log Y at 2.875m A.O.D.
Grey brown tan clay/buff coloured silt with fine sand laminae & carbonaceous lenses
Leaf band
unconformity
Leaf band
Leaf band
Dark grey-blue clay with warped leaf bands
Lag deposit of very coarse sand, gravel, twigs & shells
Sand & shell bands
Dark grey-blue clay



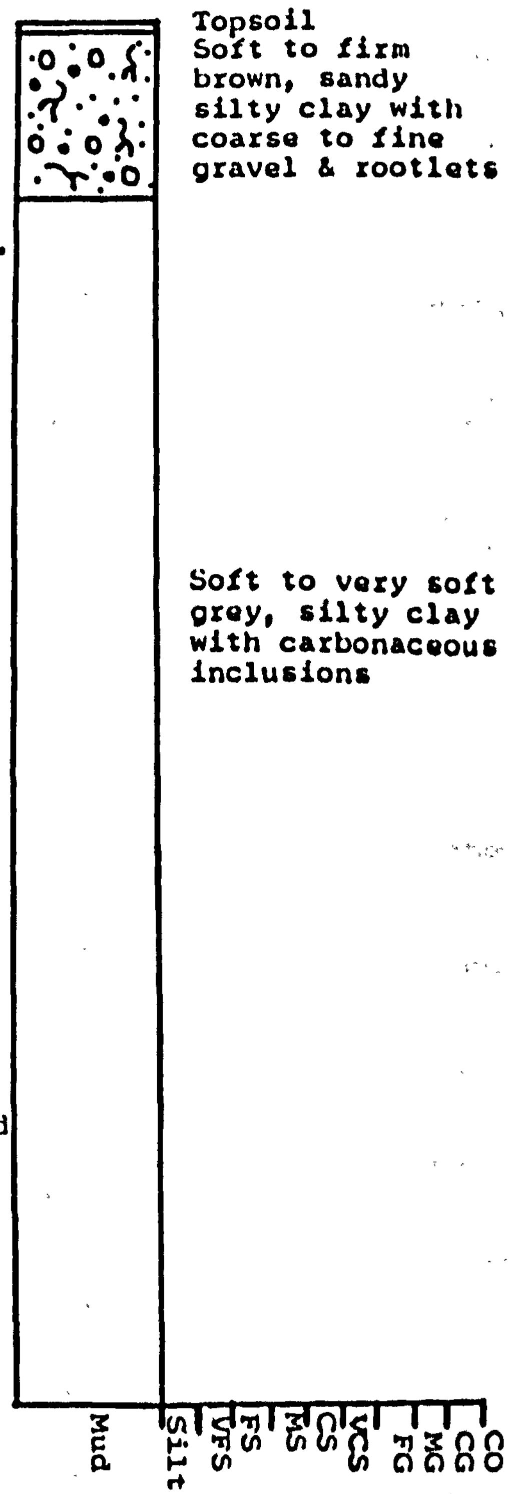
Meikle Carse Log Z at 2.725m A.O.D.



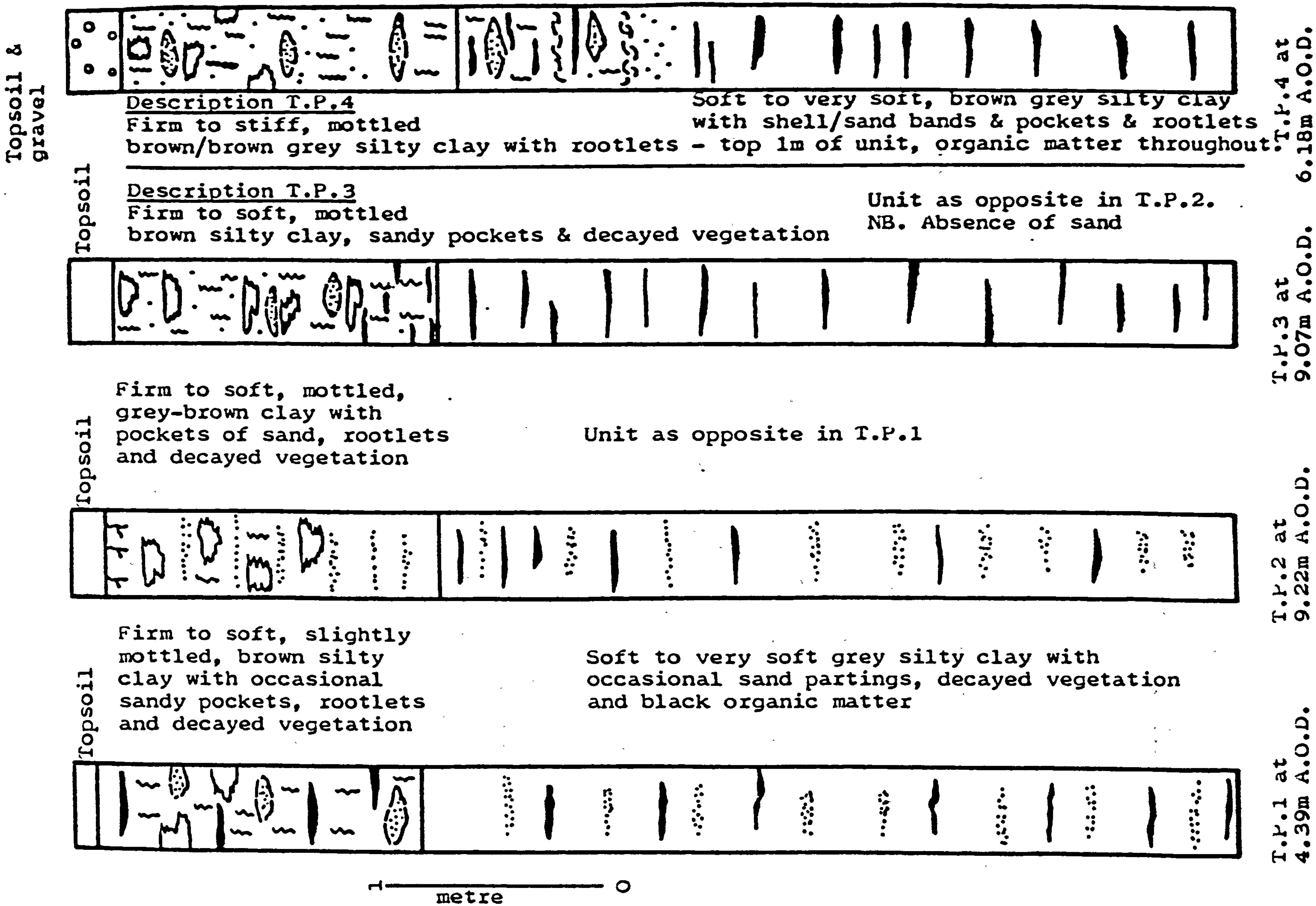
Log at Nagempsy, Palnure Burn, 7.875m A.O.D.



Borehole 1 at 4.330m A.O.D.,
A75 Boreholes, Palnure Bridge

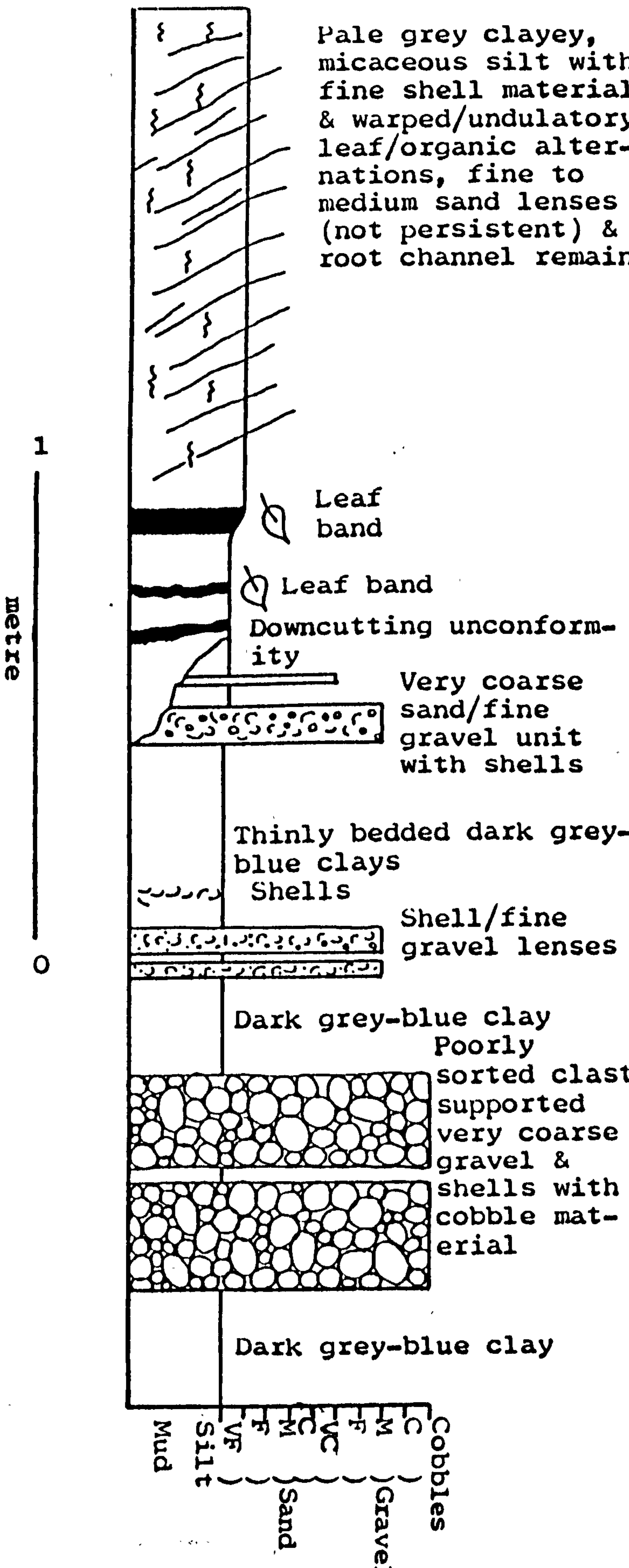


Borehole 2 at 5.520m A.O.D.,
A75 Boreholes, Palnure Bridge

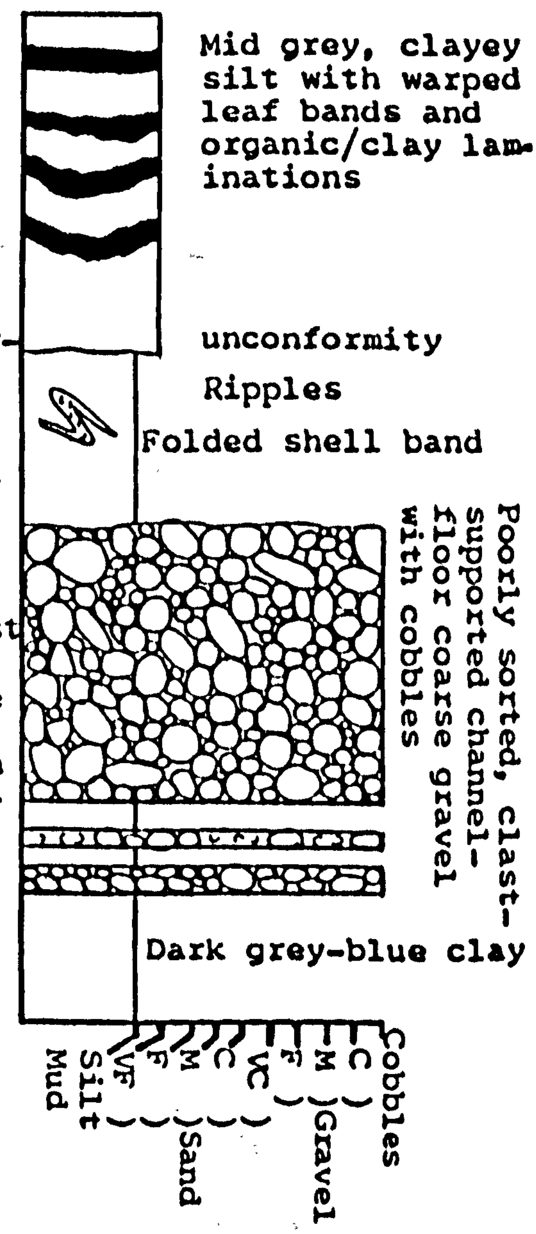


T.P.- Trial Pits. NB. Contacts between units are gradational.

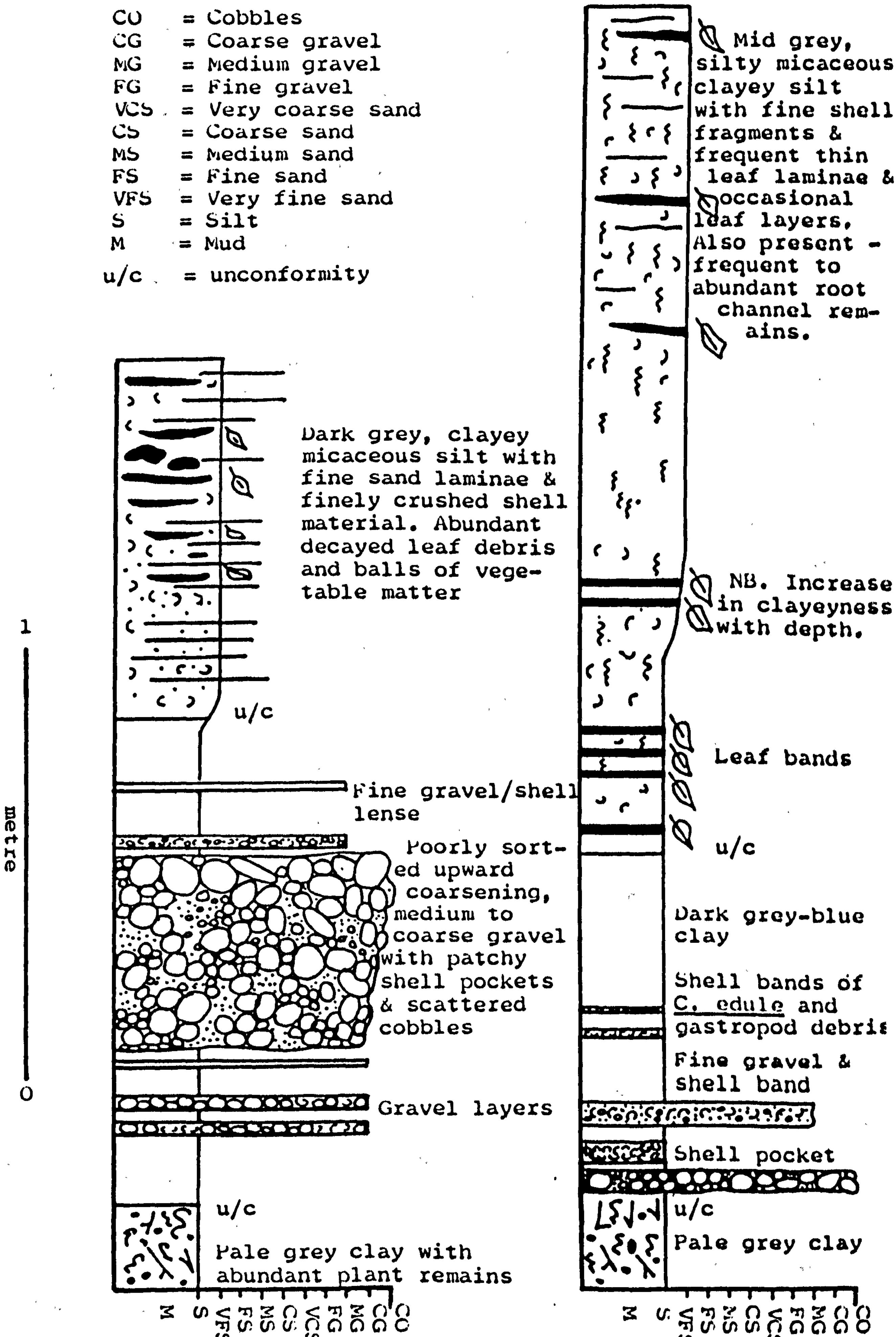
Trial Pits located along the A75 at Palnure Bridge, Palnure.



Log F, Muirfad meander, Palnure Burn, 2.265m A.O.D.

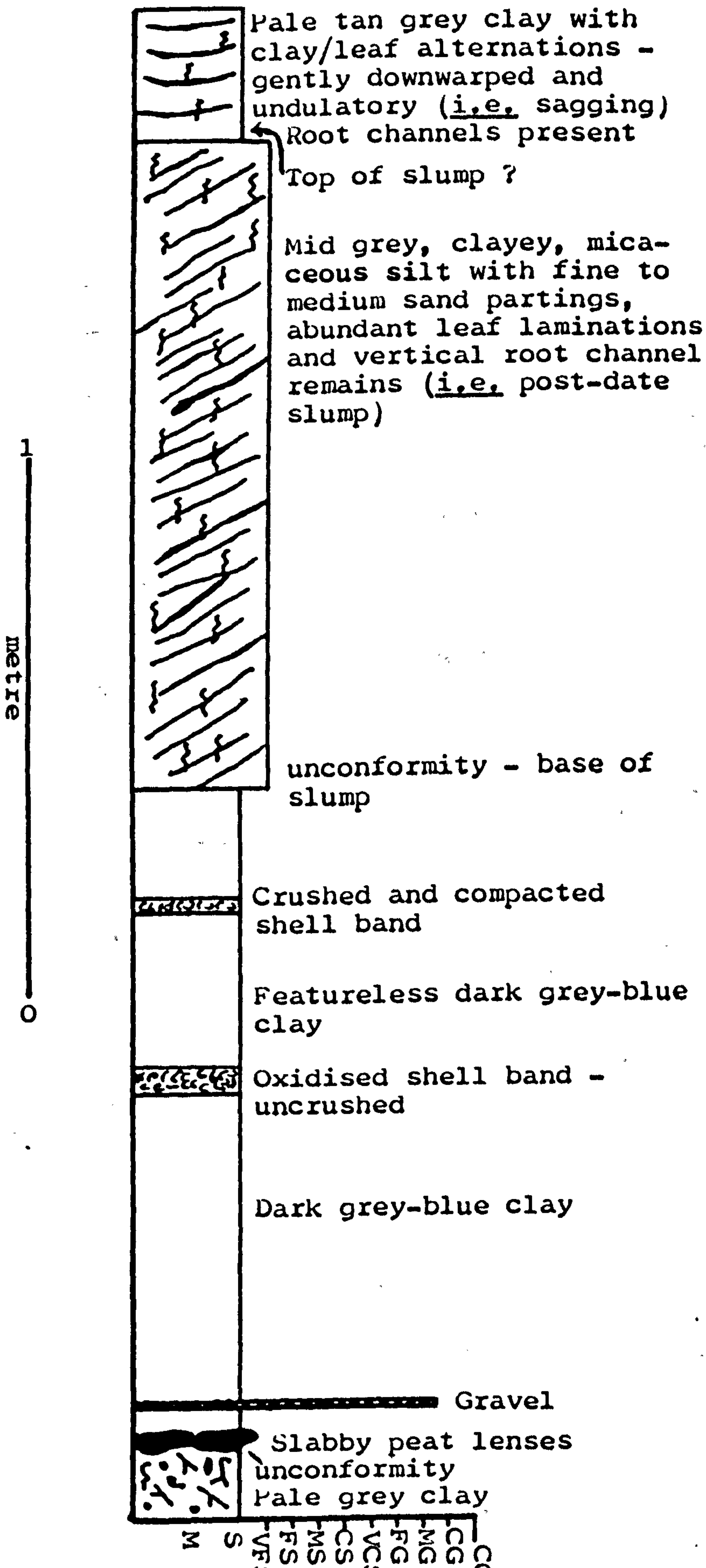


Log G, Muirfad meander, Palnure Burn, 2.520m A.O.D.

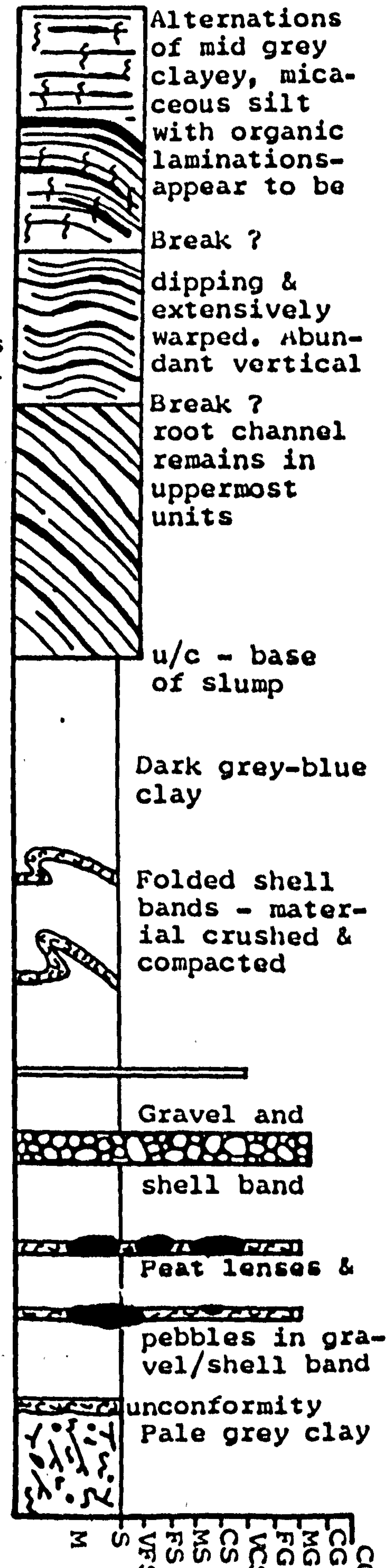


Log H, Muirfad meander, Palnure Burn, 3.080m A.O.D.

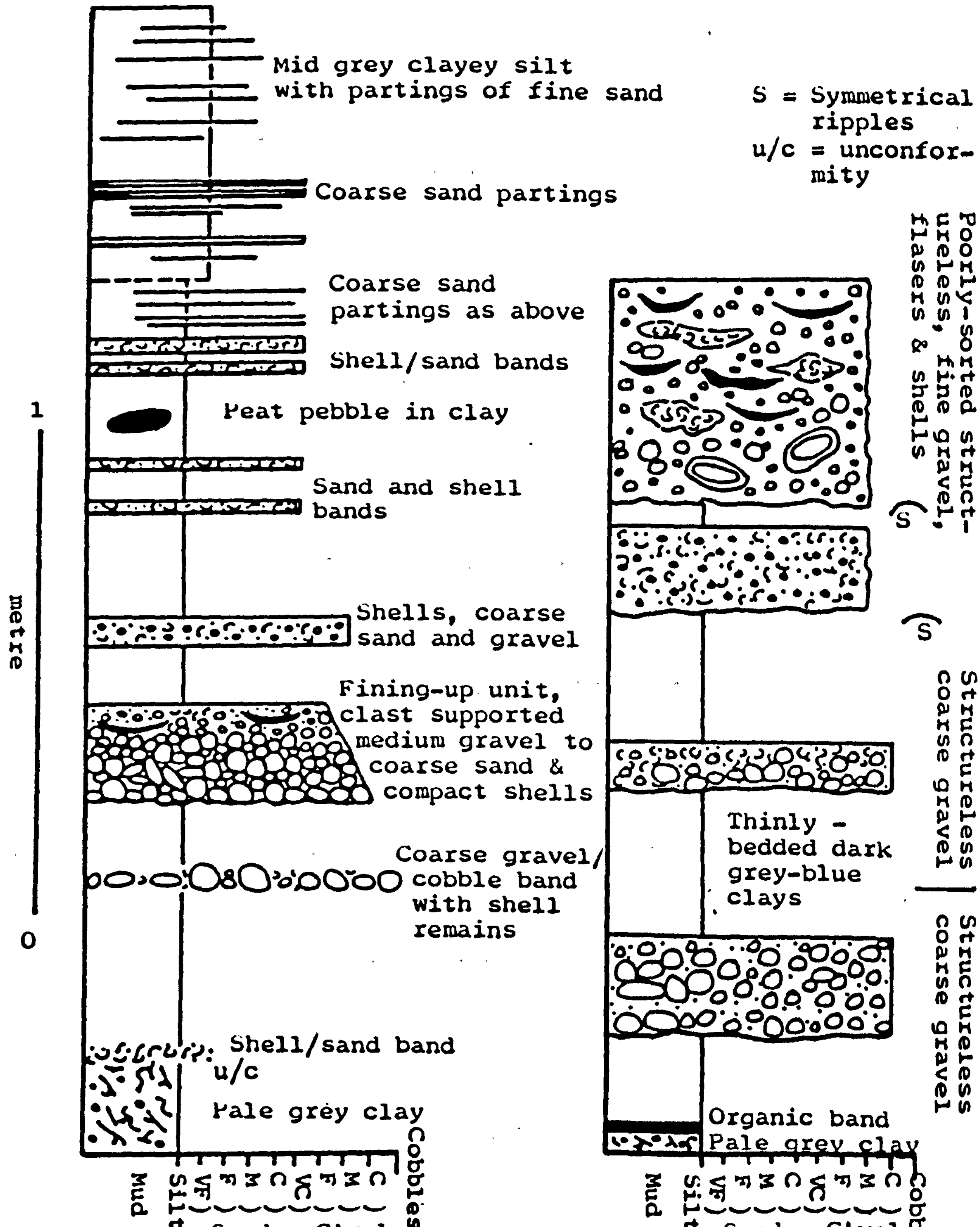
Log I, Muirfad meander, Palnure Burn, 4.460m A.O.D.



Log J, Muirfad meander, Palnure Burn, 3.770m A.O.D.

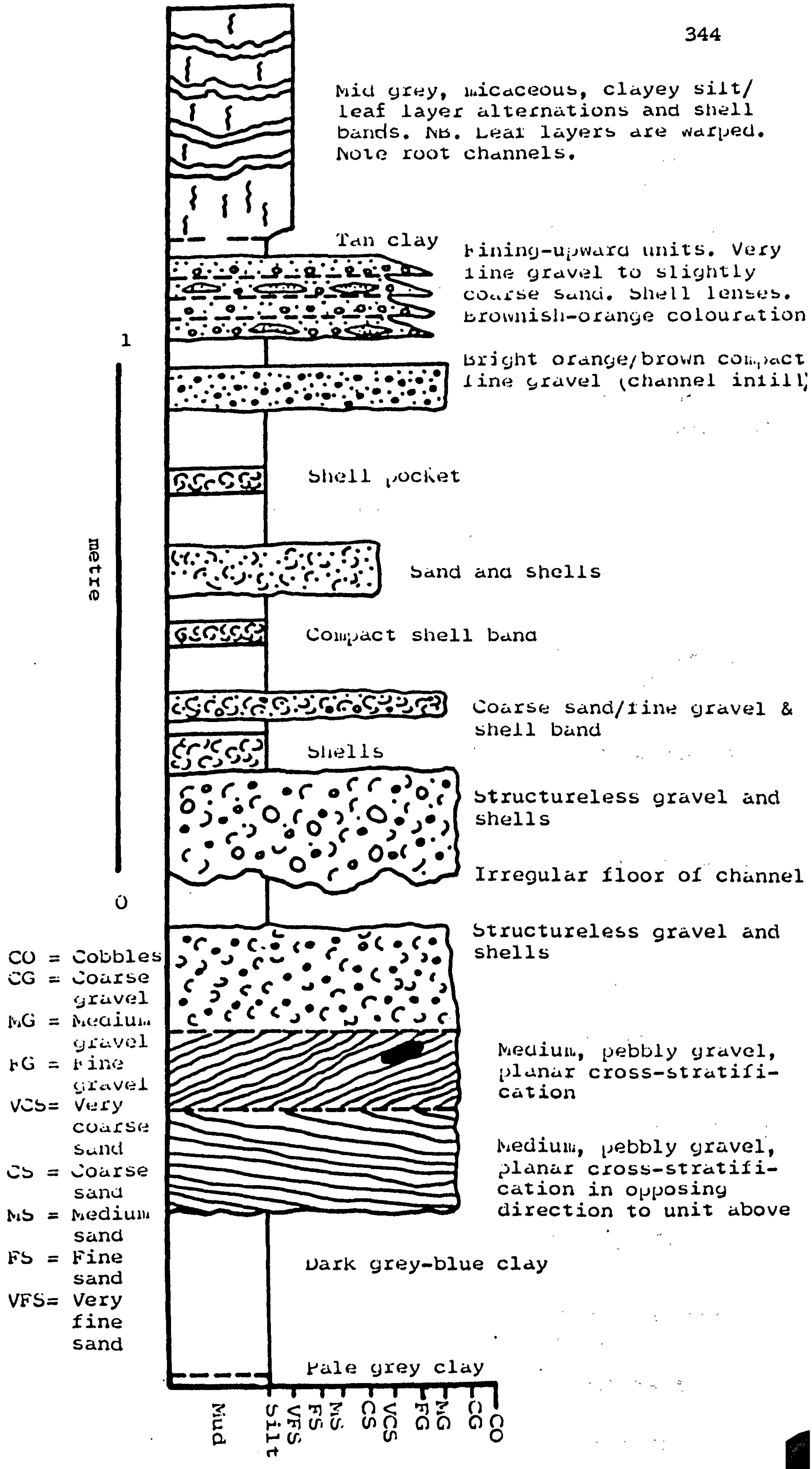


Log K, Muirfad meander, Palnure Burn, 3.780m A.O.D

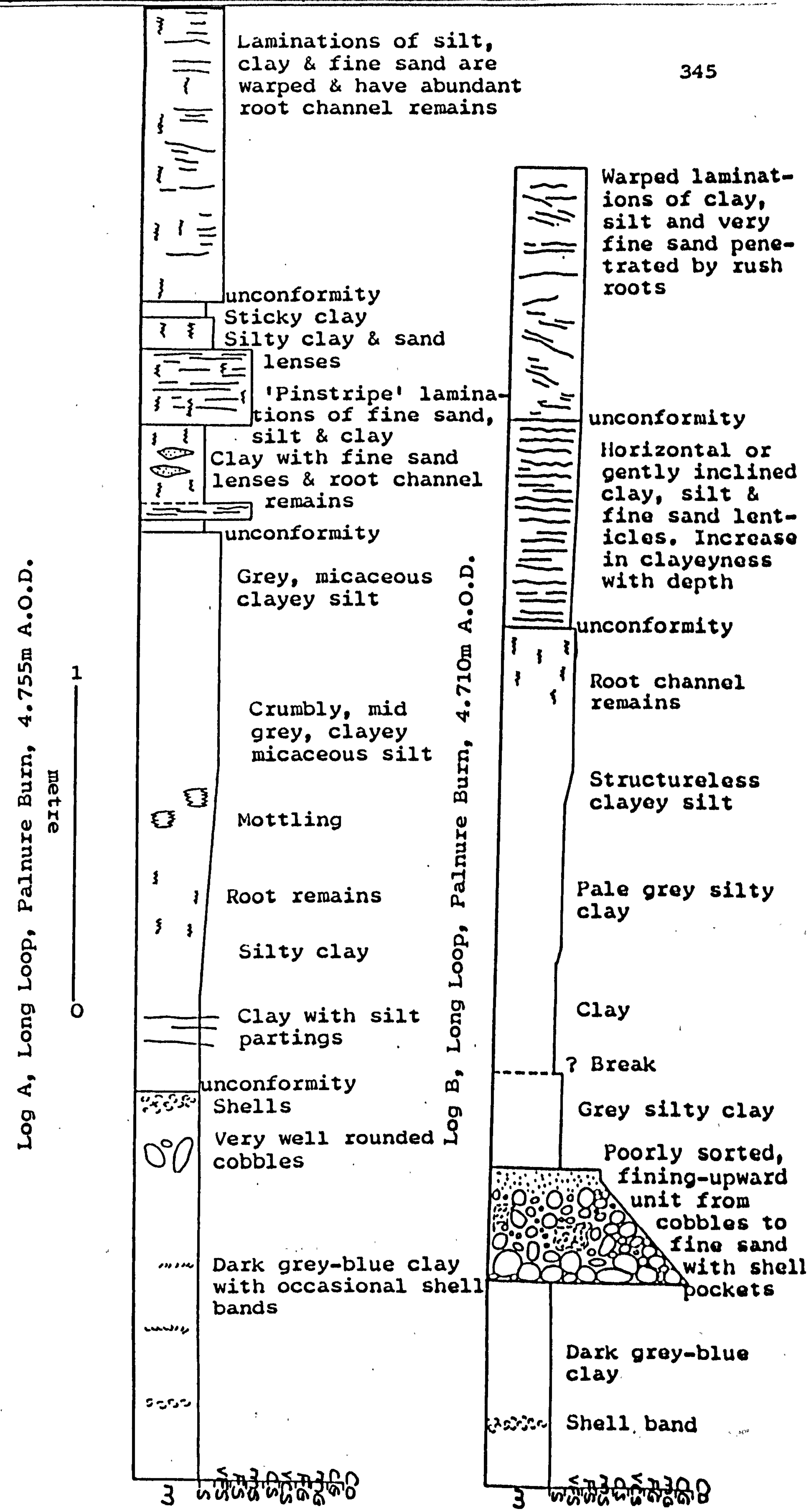


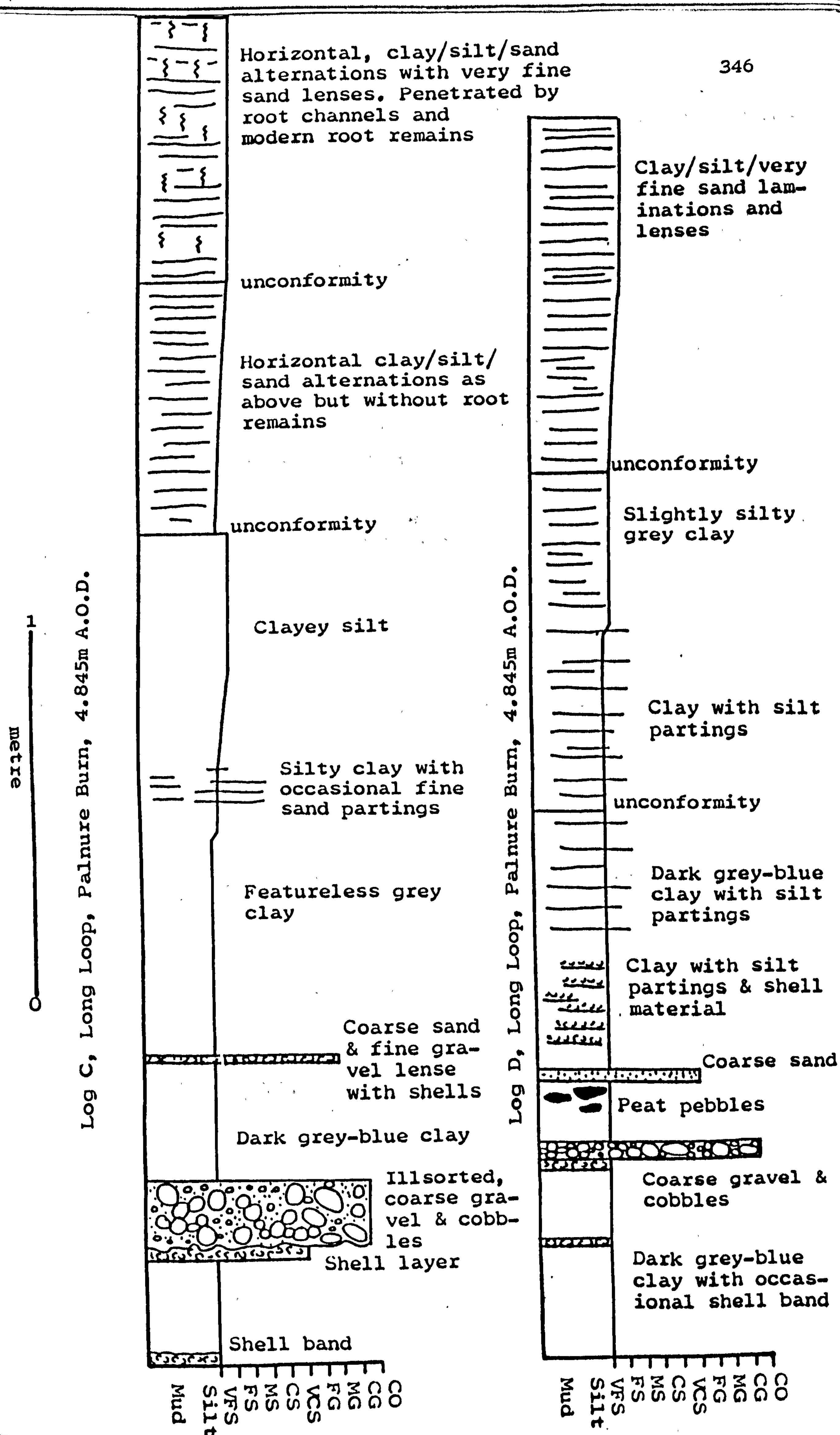
Log L, Muirfad meander, Palnure Burn, 2.940m A.O.D.

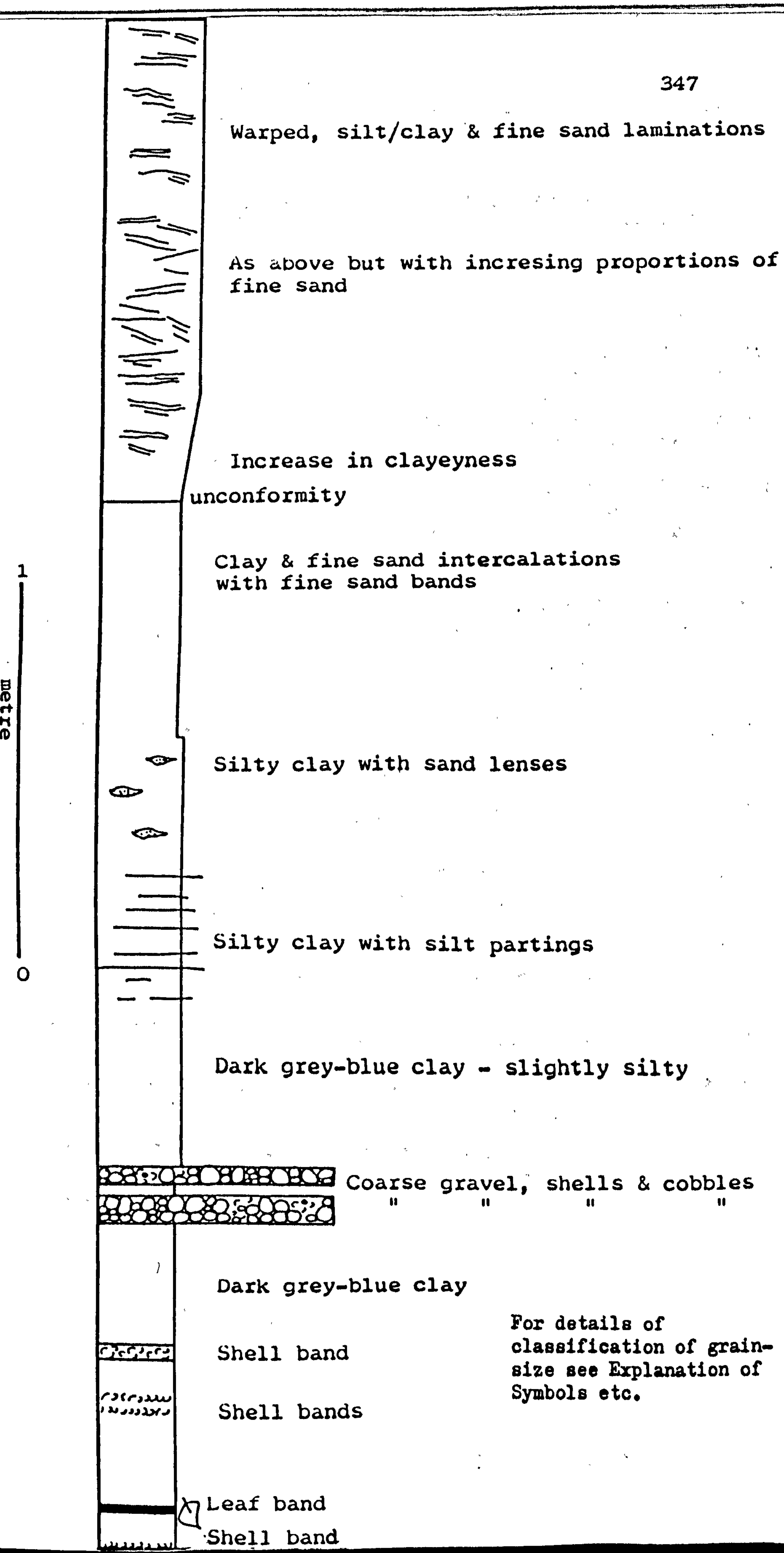
Log M, Muirfad meander, Palnure Burn, 2.260m A.O.D.



Log N, Muirfad meander, Palnure Burn, 3.205m A.O.D.

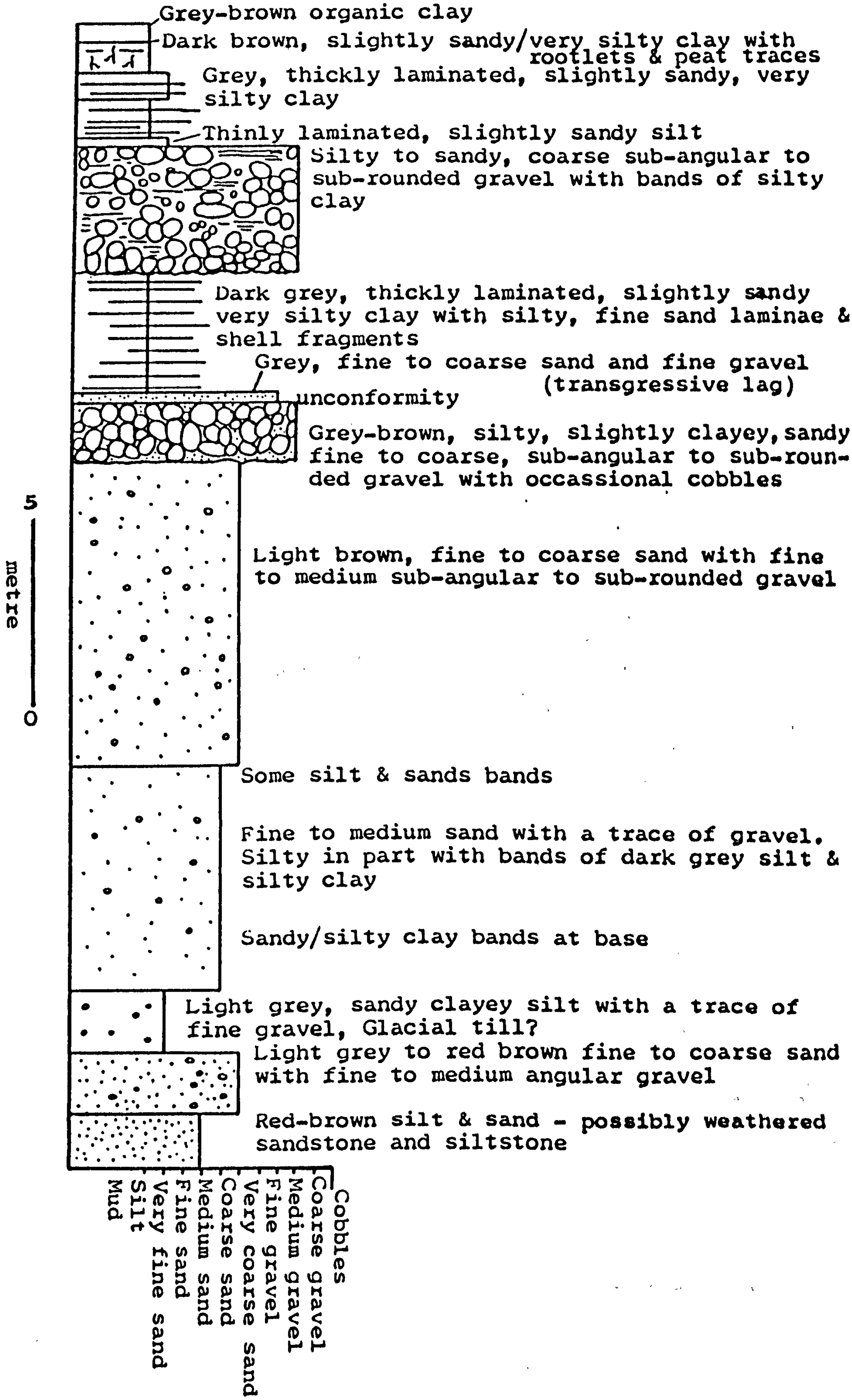

Log A, Long Loop, Palnure Burn, 4.755m A.O.D.
Laminations of silt, clay & fine sand are warped & have abundant root channel remains
unconformity
Sticky clay
Silty clay & sand lenses
'Pinstripe' laminations of fine sand, silt & clay
Clay with fine sand lenses & root channel remains
unconformity
Grey, micaceous clayey silt
Crumbly, mid grey, clayey micaceous silt
Mottling
Root remains
Silty clay
Clay with silt partings
unconformity
Shells
Very well rounded cobbles
Dark grey-blue clay with occasional shell bands
1
metre
0
Log B, Long Loop, Palnure Burn, 4.710m A.O.D.
Warped laminations of clay, silt and very fine sand penetrated by rush roots
unconformity
Horizontal or gently inclined clay, silt & fine sand lenticles. Increase in clayeyness with depth
unconformity
Root channel remains
Structureless clayey silt
Pale grey silty clay
Clay
? Break
Grey silty clay
Poorly sorted, fining-upward unit from cobbles to fine sand with shell pockets
Dark grey-blue clay
Shell band


Horizontal, clay/silt/sand alternations with very fine sand lenses. Penetrated by root channels and modern root remains
unconformity
Horizontal clay/silt/sand alternations as above but without root remains
unconformity
Clayey silt
Silty clay with occasional fine sand partings
Featureless grey clay
Coarse sand & fine gravel lense with shells
Dark grey-blue clay
Illsorted, coarse gravel & cobbles
Shell layer
Shell band
Mud
Silt
VFS
FS
MS
CS
VCS
FG
MG
CG
CO
Log C, Long Loop, Palnure Burn, 4.845m A.O.D.
1
0
metre
Clay/silt/very fine sand laminations and lenses
unconformity
Slightly silty grey clay
Clay with silt partings
unconformity
Dark grey-blue clay with silt partings
Clay with silt partings & shell material
Coarse sand
Peat pebbles
Coarse gravel & cobbles
Dark grey-blue clay with occasional shell band
Mud
Silt
VFS
FS
MS
CS
VCS
FG
MG
CG
CO
Log D, Long Loop, Palnure Burn, 4.845m A.O.D.

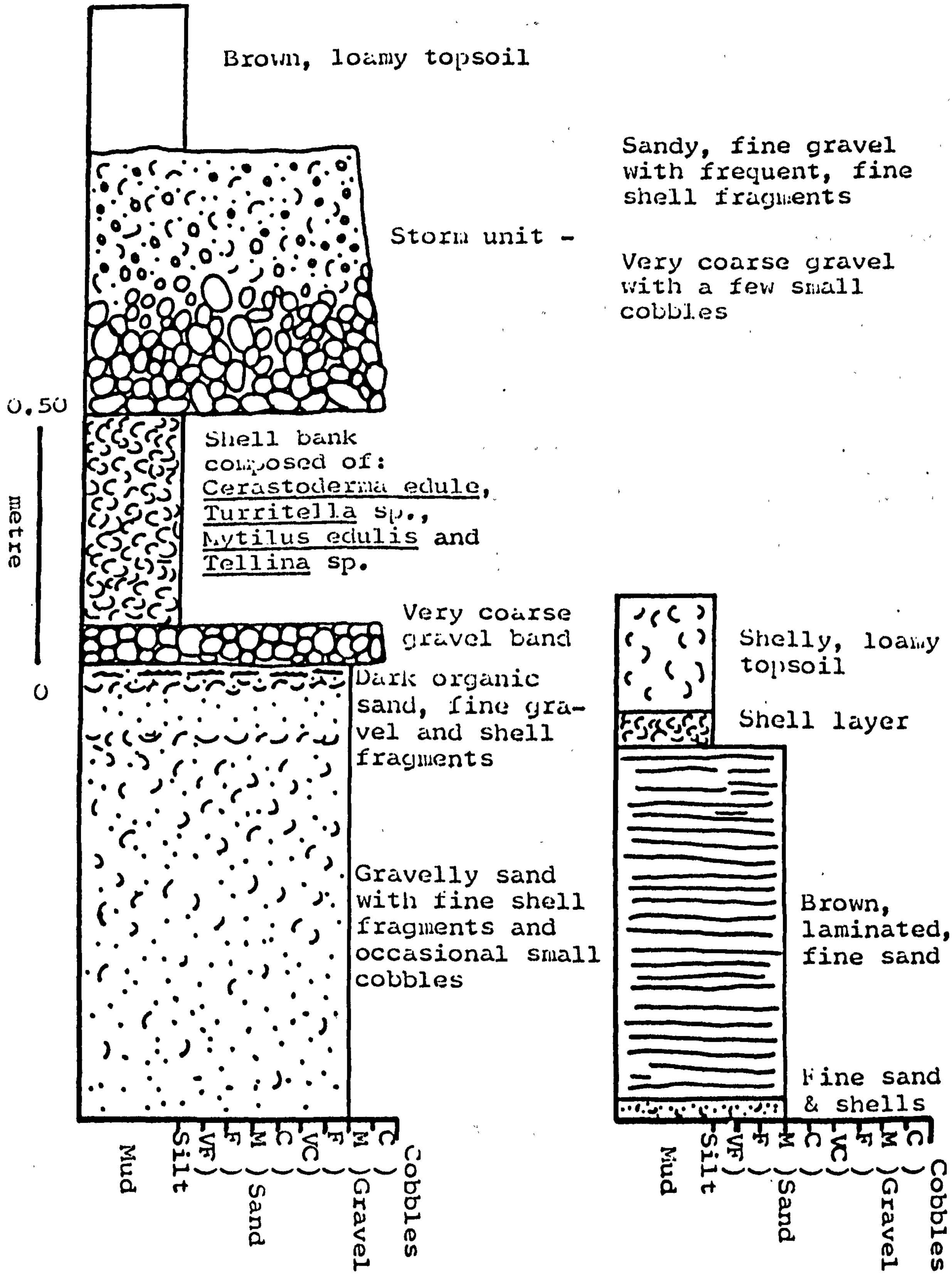


For details of classification of grain-size see Explanation of Symbols etc.

Log E, Long Loop, Palnure Burn, 4.380m A.O.D.

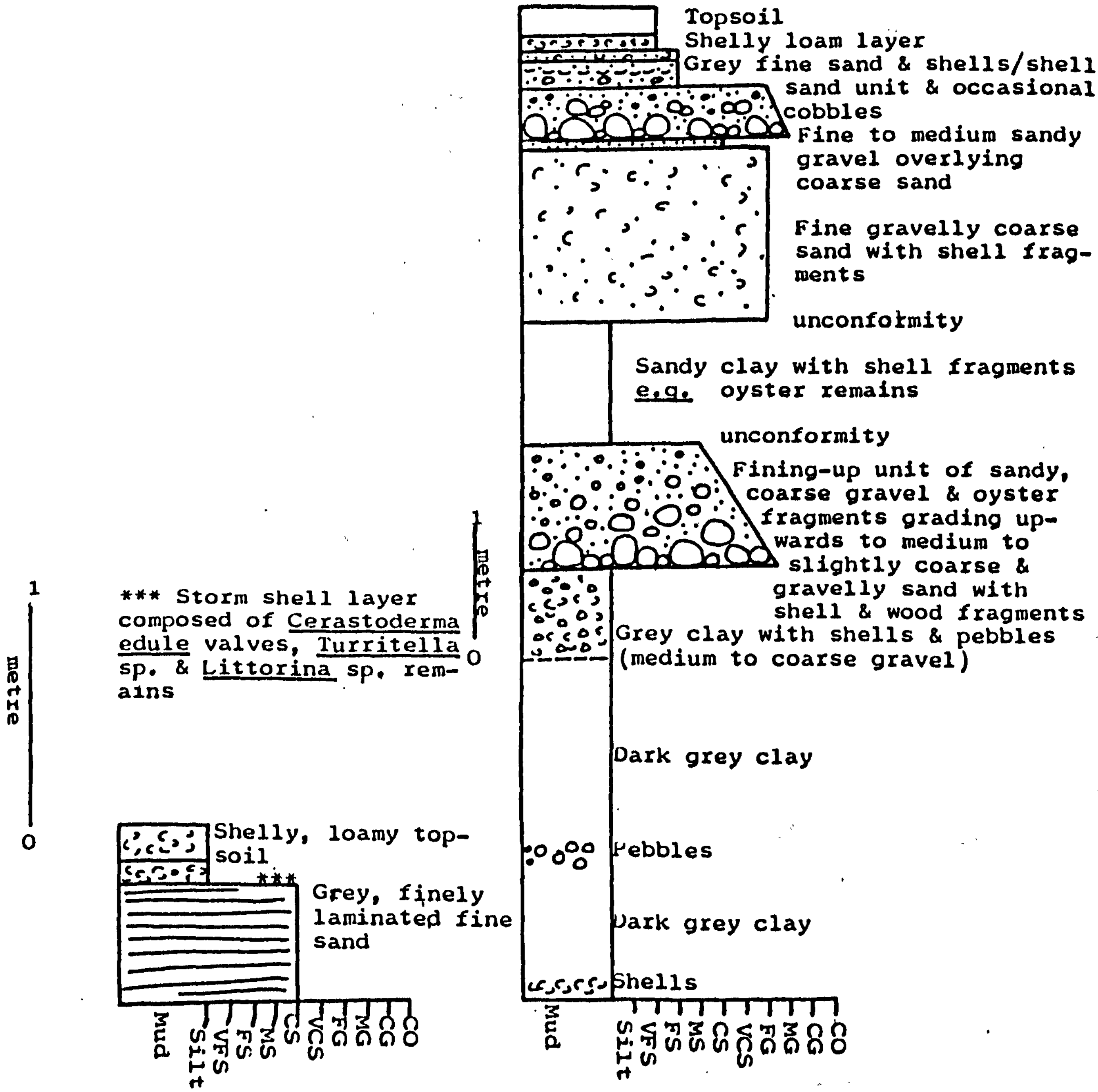


Creetown By-pass Representative Borehole, B1, at 3.74m A.O.D.



Cassencarie borehole 1
at 5.95m A.O.D.

Cassencarie borehole 2
at 6.00m A.O.D.

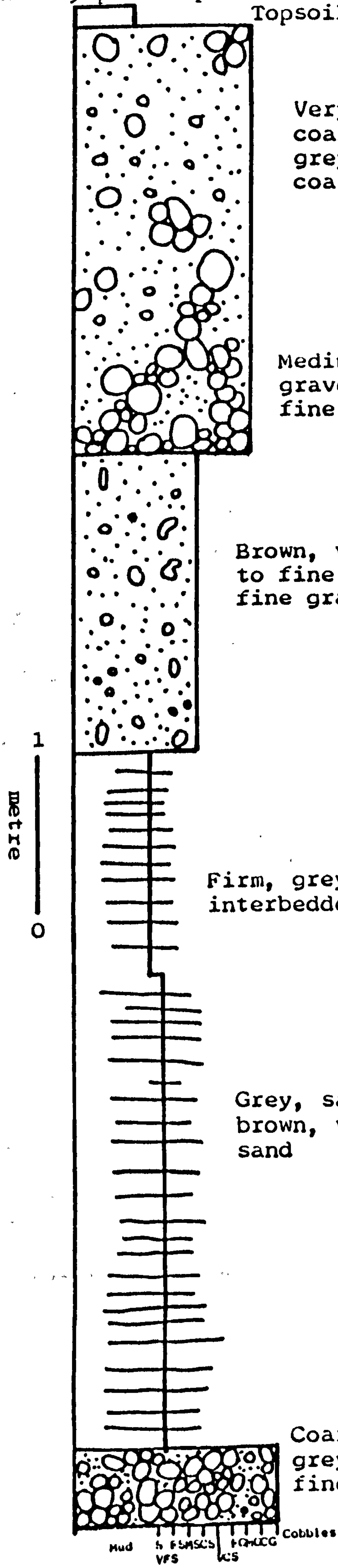


Cassencarie borehole 3 at 5.790m A.O.D.

Cassencarie borehole 4 at 5.020m A.O.D.

Carsluith By-pass representative borehole at 4.990m A.O.D.

Topsoil



Very loose to medium dense, coarse to fine gravel with grey-brown clayey silty coarse to fine sand

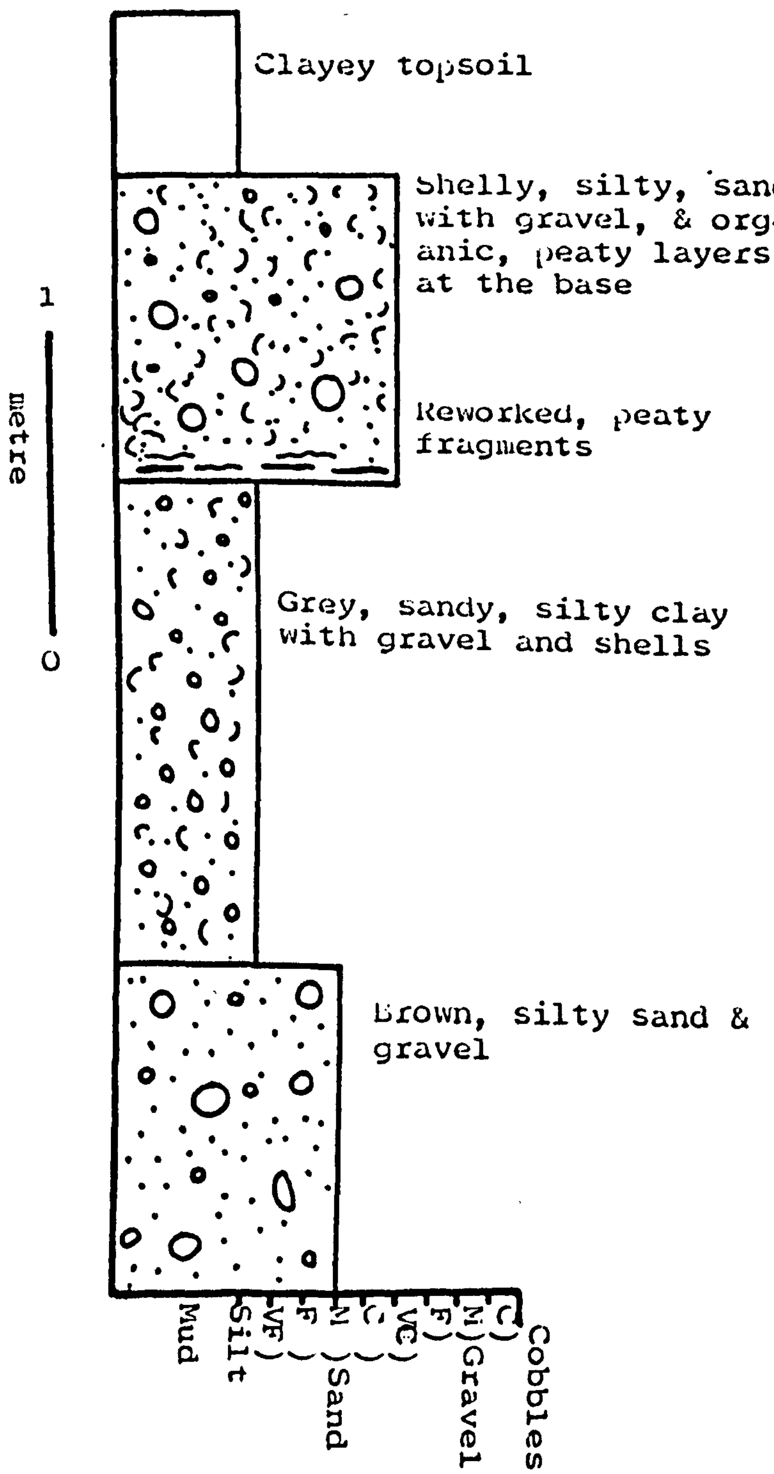
Medium dense coarse to fine gravel with grey, coarse to fine sand

Brown, very clayey silty, medium to fine sand with some coarse to fine gravel

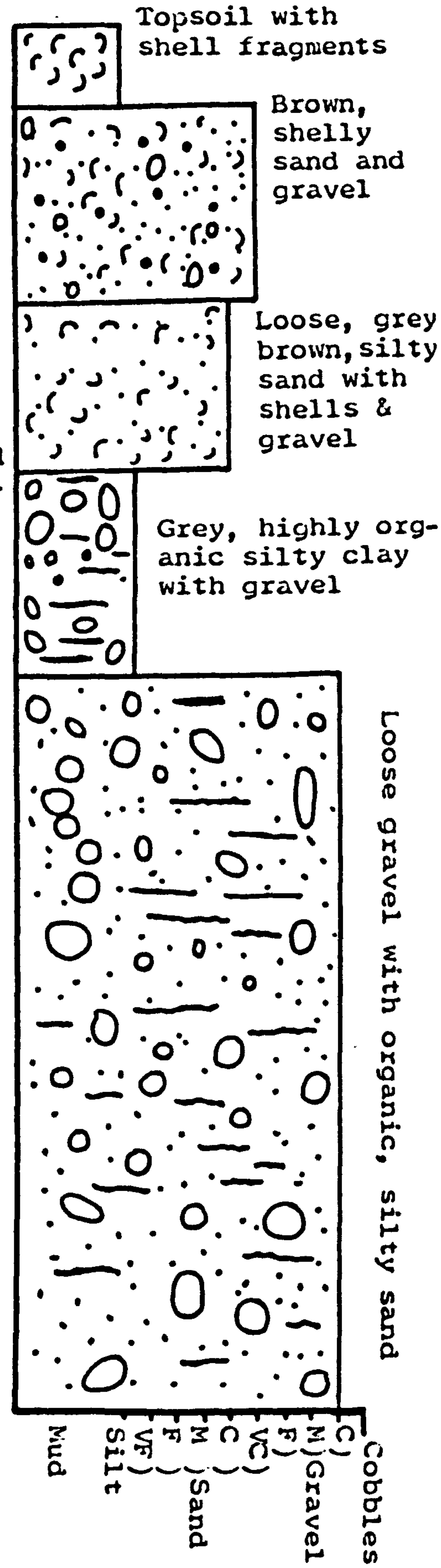
Firm, grey-brown, sandy silty clay interbedded with brown, silty sand

Grey, sandy silt interbedded with brown, very silty medium to fine sand

Coarse to fine gravel with grey, very silty medium to fine sand



Carsluith By-pass borehole
CAP 6 at 4.89m A.O.D.



Carsluith By-pass borehole
CA 7 at 5.20m A.O.D.

APPENDIX 2

APPENDIX 2.a

Point-bar facies: the Carsenestock point-bar in relation to other examples of point-bar deposits

Introduction

The key facies characteristics of the Carsenestock point-bar and its sub-environments are summarised in Figure 1 and described below (see also Chapter 10.2.3.3). A review of the literature highlights several similarities between the Carsenestock point-bar and others, and also notes major differences.

Description of point-bar facies

The major facies of the Carsenestock point-bar are described from west to east and high to low on the point-bar, in terms of lithology and the sedimentary and biological features that are present (cf. Fig. 1).

Upper point-bar

The sediment, which is loosely consolidated, is composed of fine sand (comprising c. 95% of the box-core sample), with subordinate amounts of mud The sand and mud form horizontally-bedded 'couplets', the sand being deposited as small-scale, flood-oriented ripples, exhibiting low-angled planar foresets (8^{o} - 10^{o} dip) a few millimetres in thickness. Features noted were re-activation surfaces, stoss-side preservation and reworking, climbing ripples and counter current ripple cross stratification. All the above are evidence of active ripple migration despite a weakening flood-current flow at the close of high water. No ebb-oriented features were noted.

The ripples are frequently truncated by the mud 'episode', the mud laminae being 2-4mm in thickness. Mud flasers are poorly developed.

Faecal pellet holes and vegetational wisps were also noted.

Near the bar surface, post-depositional deformation features (e.g. fluid ejection features and folding), due to disturbance of the sediments, were noted.

Mid, Upper point-bar

The sediment comprises equal amounts of mud and sand, forming alternations or lenses. The sand is of medium to coarse grade. The small-scale flood-oriented ripples are poorly developed but do show evidence of re-activation surfaces.

There is a minor amount of bioturbation in the mud intervals, with disruption of bedding by organisms. Mud drapes are also evident.

Chute Channel (mid point-bar)

The chute channel sediments are chiefly medium to coarse sands with some very coarse sands. They are loosely consolidated. Mud is virtually absent, being present only as flasers, pellets or drapes.

The sands exhibit flood-oriented planar cross stratification (10 - 15° dip) but whole ripples are poorly developed, due to frequent breaks. The cross stratification is asymptotic at its base. Plane laminations are also in evidence, confirming the high-energy nature of this sub-environment. The base of the channel is covered by typical lag deposits (twigs, shells, clay and mud discs). The lag is frequently imbricated. Herring-bone cross stratification was noted - with flood-oriented foresets more frequent than ebb-oriented foresets.

Lower point-bar and channel/channel floor

The sands are generally coarse to very coarse grade and are very loosely consolidated - often waterlogged and mobile. Mud is absent, being held in suspension by high-velocity currents. Structures comprise coarse lags with poorly developed herring-bone cross stratification. Unidirectiona planar cross stratification is found in ebb-oriented channel-floor dunes. These have a low preservation potential because structures are more often than not eliminated by succeeding flood tides.

General features of the point-bar

It was noted that the orientation and form of sedimentary structures on the bar surface were complex and variable due to the sinuosity of the meander, flow differences over the curved bar surface (resulting in interference of the pattern of structures) and superimposed late stage drainage features.

Under regressive marine conditions and infilling of the Upper Cree estuary, point-bar migration proceeded in a north-eastwards direction, generating the following fining-upwards vertical sequence (c. 4m in thickness), from top to bottom. Such a sequence is likely to be preserved in the geological record.

1. Marsh
Thinly laminated sands, silts and clays with vegetational matter
2. Upper point-bar (sandy)
Small-scale flood-oriented ripples in fine to medium sand interbedded with muds; minor bioturbation
3. Mid, Upper point-bar (mixed sand and mud)
Sand and mud laminations, layers, lenses, ripples and mud drapes; frequent bioturbation
4. Chute channel
Medium to very coarse sands, large-scale planar cross sets, flasers, herring-bone cross stratification interbedded with lags; minor amount of mud; no bioturbation
5. Lower point-bar
Large-scale planar and herring-bone cross stratification in coarse to very coarse sand; lags evident; no bioturbation or muddy sediment
6. Channel/channel floor
A repeat of the above-described unit 5

Discussion

A review of the relevant literature allows similarities and differences to be noted between the Carsenestock point-bar and other point-bars. Land and Hoyt (1966) attempted to define the differences between fluvial and estuarine sediments by analysing point-bar deposition in a meandering river setting. A broadly similar study of point-bar structures at Carsenestock revealed that there existed in the process of deposition more similarities than differences between fluvial and estuarine deposits, thus complicating the interpretation of the geological record.

The Carsenestock meander and adjacent point-bar appears to correspond with meander type 'C' of Bridges and Leeder (1976, p. 547 and Fig. 17, p. 548), a tight, acute-angled bend with distinctive depositional and erosional pattern on the point-bar as a result of the onset and intensity of confined flow separation.

In the River Cree adjacent to Carsenestock, flow separation becomes progressively pronounced as the ebb proceeds, flow becoming confined to the main channel early in the ebb phase. The long duration of the ebb – 9 hours in the Cree – enhances the flow separation effect.

The confined flow leads to rapid retreat of cut banks and to rapid advancement of the lower point-bar toe or platform. Exceptional and high stage flow (both ebb and flood) has created a chute channel which separates the lower point-bar platform from the remainder of the point-bar.

It was noted by Land and Hoyt (1966) that, in Blackbeard Creek, ebb-oriented sedimentary structures predominate. The opposite is true of the River Cree at Carsenestock (where flood-oriented features are dominant), although the ebb is of similar duration to that at Blackbeard Creek.

At Blackbeard Creek, once the point-bar is uncovered by the falling ebb, all flow is restricted to the main channel, as is that of the Carsenestock bar and adjacent channel, although there may be a very weak ebb flow in the chute channel at Carsenestock at this stage. This is especially true at times when fluvial discharge enhances ebb tidal flow.

Bimodal features (herring-bone cross stratification) recorded at Blackbeard Creek are also present on the lower point-bar at Carsenestock, but are not very well developed on the latter.

The lower point-bar deposits in both cases were very unstable after exposure. Deformed cross bedding was noted at Blackbeard Creek but was absent at Carsenestock because the low point-bar deposits are very loosely consolidated and internal structure is poorly defined.

At Blackbeard Creek a complete set of ripples was present, due to oscillatory flow. Ladder and wind shear ripples were arranged normal to the crest lines of the 'original' ripples. Such features were also recorded on the flanks of the Carsenestock point-bar. All symmetrical current ripples preserved in the Carsenestock upper and mid point-bar box cores were flood-oriented, whereas 95% of the cross beds at Blackbeard Creek were ebb-oriented. Flasers were noted in the chute channel deposits at Carsenestock. These were simple, poorly developed and not particularly abundant, possibly because they were destroyed by subsequent (ebb) tidal flow. Langhorne and Read (1986), working on the relationship between intertidal and sub-tidal bedforms in the Taw-Torridge estuary of North Devon, noted that, although there was much clay and silt in suspension and the potential for the development of flaser bedding was high (as it was on the Carsenestock point-bar), flasers are poorly preserved. This suggests strongly that these structures are constantly eradicated by high tidal flow velocities.

Langhorne and Read (1986) also discussed mud drapes. These are evident in the chute channel and mid upper point-bar facies at Carsenestock and are products of slack-water deposition. Langhorne and Read noted reversal of structures under tidal flow, with or without erosional discontinuities. This was also evident in the chute-channel box cores at Carsenestock.

Langhorne and Read (1986) also commented upon the large-scale or 'master bedding' recorded in the Taw-Torridge estuary. 'Master bedding' may be attributed to a certain 'event', possibly the influx of a large quantity of a particular type of sediment. This was not evident on the River Cree, where it is difficult to establish whether the internal structure of bedding of the lower point-bar is that of low angle cross stratification or is the inclined (accretionary) bedding-surface of the point-bar. De Mowbray (1983) has discussed the genesis, morphology and structure of lateral accretion deposits in detail within the context of changing tidal flow, taking into account the effects of season and weather conditions. Her detailed account of the development of point-bars (De Mowbray 1983, p. 431) treats successfully the concept of event-bedding.

The fining-upwards sequence of the Carsenestock point-bar conforms with the general pattern of comparable point-bar deposits, having characteristics similar to the 'riverine estuary' and 'salt-marsh estuary' sequence proposed by Howard and Frey (1980, pp. 224-231). The Carsenestock sequence probably is closest to the 'riverine estuary' sequence, in which the presence of interbedded sand and mud reflects the increased interaction between estuarine and fluvial-type processes. The 'riverine estuary' sequence is as follows, from top to bottom:

1. Bioturbated and mottled sandy mud - marsh
2. Bioturbated, muddy fine sand - channel margin
3. Ripple laminated and cross bedded sand, flaser and wavy bedding - point-bar, tidal-flat and shoals
4. Laminated mud, interbedded sand and mud, laminated wavy and flaser bedding - estuarine accretionary beds
5. Cross bedded medium and coarse sand with lenses of pebbles - channel lag and lower part of channel fill

A similar regressive estuarine sequence was proposed by Greer (1975):

1. Roots, silt and clay - saltmarsh
2. Muddy sand, bioturbated, flaser structures, fine sand, laminated sand - tidal-flat

3. Muddy sand, bioturbated - shallow channel
4. Planar foresets with mud pebbles, wavy bedding, ripples, muddy coarse sand, bioturbated laminated mud, planar foresets, coarse sand - channel bar and channel bottom deposits
5. Gravel, shell debris - channel lag

The point-bar sequence at Carsenestock exhibits elements of all the units listed by Greer (1975). Greer's unit 2 (tidal-flat) is the equivalent of the upper and mid upper point-bar deposits at Carsenestock, whilst unit 3 (shallow channel) is broadly comparable with the chute channel. Units 4 and 5 (channel bar, bottom and lag deposits) are equivalent to the Carsenestock lower point-bar and adjacent channel of the River Cree.

In summary, the key differences between the succession at Carsenestock and that in other areas discussed above are that at Carsenestock there is a lack of:

1. Bioturbation, and fauna in general
2. Preserved exposure features
3. Ebb-oriented features on the upper point-bar.

A distinctive feature noted in the Carsenestock deposits was herring-bone cross stratification, indicating tidal flow reversal. This feature, however, is not considered diagnostic of sedimentation on a point-bar. To enable point-bar deposits exhibiting such a feature to be identified in the geological record, the sequence would have to be studied in relation to the deposits of adjacent facies and environments.

APPENDIX 2.b

Tidal-flat facies: the Moneypool Burn tidal-flat in relation to other examples of tidal-flat deposits

Introduction

The major facies characteristic of the Moneypool Burn tidal-flat sub-environments at Creetown are summarised in Figure 2 and described below (see also Chapter 10.3.2.1 to 10.3.2.4). In a review of recent literature, several similarities and differences were noted between the deposits at Creetown and tidal-flat deposits studied elsewhere.

Description of the tidal-flat facies

The major tidal-flat facies are described from NE to SW and from a high to low position (*cf*. Fig. 2), the lithology, sedimentary structures and biological features that are present being noted.

Westward progradation of the tidal-flat at this point, due to infilling of the estuary, would produce the following vertical depositional sequence, from top to bottom:

Marsh

Thinly laminated muds (80% clay) interbedded with vegetational matter; extensive bioturbation by *Corophium volutator* on exposed muddy areas.

Mixed sand/mud flat

Well laminated silts, clayey silts and fine sands; abundant plant and shell debris; extensive bioturbation.

Scour depression (infilled in vertical sequence by mixed sand/mudflat or sand bar deposits)

Widespread lag deposits composed of branches, twigs, leaves, shells and pebbles; small-scale flood-oriented ripples in sand.

Sandbar

Small-scale flood-oriented ripples in medium to slightly coarse sand, wind shear ripples on bar surface, sandy flasers; intense bioturbation in clayey intervals.

Channel

Coarse to very coarse sand, herring-bone and planar cross stratification (both poorly developed) and structureless sand.

Discussion

Tidal-flat environments have been and are being extensively studied, and are well documented. An outstanding feature, common to all tidal-flat settings, is the characteristic horizontal zonation of the fining-upwards sequence, from generally coarser grade sand flats at low water mark through to muddy upper tidal-flats and marsh deposits. Such zonation is discussed by Evans (1965) in relation to the Wash area of Eastern England, and by Reineck (numerous papers) in relation to the North German tidal-flats. Reineck (1972), indeed remarked, 'The horizontal sequence of a given environment means inclined, laterally associated depositional regions which during progradation may grow one above the other'.

Under regressive conditions (i.e. at present), a prograding shoreline would produce the typical tidal-flat sequence, from top to bottom:

1. Peat
2. Freshwater and brackish-water deposits
3. Saltmarsh
4. Mud-flat deposits
5. Mixed-flat deposits
6. Sandflat deposits.

In many cases the recent tidal-flat sequence is not fully developed for various reasons. In the case of the Moneypool Burn tidal-flat, only units 3, 4 and 5 of the above sequence are in evidence (the sandbar located in the channel of the River Cree is of mixed-flat type).

Because of the widely variable nature of tidal-flat deposits and processes of deposition, comparisons between tidal-flats of one area and another are extremely difficult. Selected studies of other areas, however, are compared below with the deposits of the Moneypool Burn tidal-flat at Creetown.

Kellerhals and Murray (1969), working in Boundary Bay, south of the Fraser River Delta, British Columbia, described a predominantly sandy tidal-flat environment with subordinate amounts of silty and sandy muds. The tidal-flat at Creetown is of mixed sand and mud composition. The sediment source in Boundary Bay is terrigenous, as opposed to that of the Moneypool Burn area where material is marine-derived. There is some locally-derived material from unconsolidated Pleistocene cliffs at Boundary Bay. The situation may be somewhat similar in the case of Moneypool Burn; some material may have been derived from thick fluvio-glacial deposits that occur upstream from the tidal-flat deposits.

The marsh at Boundary Bay is located above mean high tide, as is the marsh of the Cree estuary area; flooding takes place only occasionally, at high spring tides. The marsh is traversed by incised meandering creeks. A cliffed shore marks the seaward margin of the marsh, as in the case of the Cree estuary.

The sediments of the saltmarsh at Boundary Bay comprise poorly stratified, massive brown peat and silty clay. The marsh surface is vegetated by halophytes. The marsh sediment at Creetown is composed of 80% muds interbedded with vegetational matter. The halophytes in both areas act as sediment traps during storm conditions. At Creetown, extensive bioturbation is prominent on the unvegetated margins of the marsh and channels. Storm shell concentrations are evident on the marsh at Boundary Bay but are absent on the Moneypool Burn tidal-flat. Peat accumulation is taking place at Boundary Bay, but only peat traces are found within the saltmarsh deposits at Creetown.

In the eastern part of Boundary Bay, at Mud Bay, the saltmarsh/tidal-flat junction is marked by a cliff c. 0.6m in height. This is similar to the situation at Creetown. In the western part of the Bay, the boundary between the marsh and tidal-flat is transitional to the sandy flat. The seaward margin of the marsh is hummocky, and there is steady accumulation of sandy sediment between the hummocks. This is similar to the situation at the marsh edge at Creetown.

The high tidal-flats of Boundary Bay are sandy, not extensively bioturbated and they are channelised by shallow depressions oriented parallel to the shore. At the equivalent 'position' in the Moneypool Burn area, the sediments are mixed sand and mud, these being extensively bioturbated. The mixed flat is flanked by a scour depression that is oriented parallel to the shore.

A sandbar is located on the low tidal-flats flanking the main channel of the River Cree at Creetown. De Vries Klein (1970) reported the occurrence of similar linear sandbars. For the sandbars of the Minas Basin, Nova Scotia, he proposed 14 different facies, two of which are found on the sandbar of the River Cree, namely his medium sand current ripple facies and fine sand simple sand wave facies. These facies are modified on the River Cree by the presence of minor quantities of mud. The facies are regarded by (de Vries) Klein as diagnostic. The same author also noted the paucity of herring-bone cross stratification in the sandbars he described. Such stratification, however, is present on the Cree sandbar.

De Vries Klein (1970, pp. 1124-1125) also discussed the physical criteria by which fossil intertidal sandbar environments may be identified. He suggested that tidal currents form intertidal sandbars and rework them by both tidal current bottom shear and water-level fluctuations. This appears to have been the situation in the case of the sandbar of the River Cree at Creetown.

Current ripples are oriented in response to late-stage sheet run-off flow down the slope of sandbars. This appears to be true in the case of the superimposed features of the sandbar in the River Cree.

Examples of other tidal-flats comparable with those of the Moneypool Burn at Creetown include tidal-flats studied by Greer (1975) on the Ogeechee River, Georgia, U.S.A. These tidal-flats show swash bar and spit features, and the development of textures and structures is dominated by wave and current energy. Bioturbation is minimal in the areas studied by Greer, and that author reported that bioturbation, in fact, increases upstream, in areas of quieter energy. The Moneypool Burn tidal-flat, therefore, exhibits quite extensive bioturbation, which is particularly intensive in the upper mudflat areas and in the muddy intervals of the sandbar deposits.

Frey and Howard (1980) also discussed estuaries of the Georgia coast, pointing out that they differ from the large expanses of the German North Sea coast in being densely vegetated. They therefore are considered to be saltmarsh flats. Unvegetated flats do occur, but are relatively small in area, and they range in grain size from mudflats to tracts of sandy mud or muddy sand.

APPENDIX 2.c

The Holocene sedimentary sequences of the Upper and Lower Cree estuary in relation to other examples of Holocene sedimentary sequences

Introduction

Certain sedimentary and biological features evident in the changing vertical facies sequences of the Cree estuary area (Fig. 3) are diagnostic, allowing such sequences to be identified when preserved in the geological record. Identification of the vertical sequences is a key part in the recognition of ancient estuarine deposits.

In order to obtain a complete view of the Holocene infill sequence it is necessary to review the Upper Cree and Lower Cree estuary areas.

The sequence in the Upper Cree estuary provides details of early- to mid-Holocene infilling of the estuary, whilst the sequence as exemplified by the Creetown and Carsluith sections records the changing nature of tidal-flats - both their migration and infill - together with details of the pause in Holocene regression in the Lower Cree estuary area (Fig. 3).

Literature considering the detailed infilling of an estuary under regressive marine conditions is limited. Studies dealing with the transgressive nature of the Holocene sea-level rise and with the associated deposits and environments are more numerous. However, certain individual elements are common to both regressive and transgressive situations when discussed out of context, and a comparison can be made.

The main elements of the Holocene sequence in the Upper and Lower Cree estuary areas are described and discussed below within the context of relevant literature.

Upper Cree Estuary Area

The sequence is considered from the Holocene/pre-Holocene junction to the present-day marsh environment.

Pale grey clays

The pale grey clays with organic matter, of pre-Holocene marine transgression age, represent terrestrial or marshy conditions immediately below the surface of unconformity that marks the beginning of the Holocene marine transgression in the area. The dark grey-blue clays immediately above the unconformity have the characteristics of lower tidal-flats. The situation is similar to that of Kraft's 'Pleistocene' unconformity in Delaware, U.S.A. (Kraft 1971), where infilling of an area of irregular topography took place as a result of marine transgression. Similar infilling of hollows in the pre-transgression surface is common throughout the whole of the Cree estuary area (see also Greensmith and Tucker 1973, p. 193).

Kraft reported that identification of the Pleistocene surface in Delaware was a problem if the surface was located between a soil zone and marsh deposits (the differences between the characteristics of such units being subtle). This was not a problem in the Upper Cree area as the characteristics of the sediments on either side of the unconformity were so different. This is also true of the Lower Cree estuary area, where the junction is between glacial and non-glacial deposits.

The following criteria, outlined by Kraft for identification of the position of the Pleistocene surface in Delaware, are applicable in the Cree area:

1. There is a change in the characteristics of the sediments (mottling, oxidation, plant debris, etc.) across the surface; e.g. there is abundant plant debris immediately below the unconformity, but none immediately above.
2. Below the surface, the muds are compacted and their coloration is distinctive. In the Cree area, below the unconformity the sediments are pale grey clays of stiff texture and with abundant organic matter, whereas soft, dark grey-blue clays with shell remains are present above the unconformity.
3. The position of the surface corresponds closely with the areal distribution pattern of the Holocene and 'Pleistocene' sedimentary units. The relationship between the Holocene and adjacent fluvio-glacial deposits in the Cree area is well documented.

The thickness and areal extent of the Holocene sediments is controlled by the underlying topography. Although true of the Upper Cree estuary area, this is particularly noticeable in the Lower Cree estuary area where infill of hollows is marked and the areal extent of deposition is restricted to a narrow strip by the presence of a backing cliff at c. 10m A.O.D. (see p. 5 of main text). Lateral distribution of environments consequently becomes fragmented.

Low to high tidal-flats

The lower tidal-flats of the Upper Cree estuary area comprise dark grey-blue clays interbedded with gravel sheets, layers or wedges, with shells. Commonly, the gravel sheets with shells are consolidated or semi-consolidated and are highly oxidised. Greensmith and Tucker (1973) considered such 'overconsolidated' layers in the Blackwater estuary, Essex, within the context of geosol production under regressive conditions. It was suggested that the gravel pavements of the lower tidal-flats were exposed for lengthy periods. Formation was considered to be a result of storm deposition with derivation from offshore shell banks and sheets (Greemsmith and Tucker 1969). The material is initially transferred onto the lower tidal-flats from adjacent channels, and re-deposited on the upper tidal-flats as smaller-scale ridges during further storm periods.

Allen (1987b), working on the Upper Rumney Formation of the Severn Estuary, recorded three discrete sheets of sand that exhibited cross bedding. Each sheet had a sharp base and fined upwards. Allen attributed these sand sheets to storm deposition.

It appears, therefore, that the composite shell/gravel pavements of the Upper Cree estuary were formed during storm conditions, but were periodically exposed to subaerial weathering.

In considering the Upper Wentlooge Formation (which underlies the Rumney Formation), Allen (1987b) described a sequence of estuarine muds exhibiting features similar to those present in the upper tidal-flats of the Upper Cree estuary. Allen noted the presence of a peat containing birch (Betula) leaves, these also being abundant in the Meikle Carse leaf layers. A palaeosol was also developed, exhibiting a hard, resistant clay band (orange, mottled clays) similar to the 'hardpan' of the Meikle Carse sequence at Blackstrand. Root channels (of Phragmites reeds) were plentiful, as they are throughout the Upper Cree estuary area. The rarely-noted manganiferous growths covering the root channels in the Wentlooge Formation were also observed on the banks of the River Cree at several locations.

Contrasts also may be noted between the deposits of the Severn and Cree estuaries. The greenish grey silty clays of the Upper Wentlooge Formation differ in colour from the (dark grey-blue) clays of the Cree area. Also, the clays of the Severn estuary are unlaminated and poorly stratified, whereas the clays of the Cree estuary are distinctly horizontally stratified.

It also appears that Allen recorded a relatively more marine fauna in the Upper Wentlooge Formation than that which is evident in the Meikl Carse section. A possible reason for this is that the area of deposition in the Severn estuary was more 'open' to marine conditions than that of the Upper Cree area.

Very high tidal-flats and marsh

These comprise finely-laminated alternating clays, silts and fine sands penetrated by root channels (previously discussed). Shell layers are thinner than at lower levels. Organic spots and streaks are present, as is vivianite, which is commonly associated with decomposition of vertebrate debris in peat-rich marsh/estuarine clays (Greensmith and Tucker 1973).

Green, medium to coarse silty sand layers were identified in the upper parts of the Meikle Carse section but were not studied in detail. Greensmith and Tucker (1973) considered these 'puzzling' features and attributed their origin to subaerial processes, the sediments having accumulated in stagnant pools or alluvial flats under terrestrial conditions. This appears to be in accord with the view taken in the course of this work that, at the close of regressive conditions in the Upper Cree estuary area, the environment constituted a broad expanse of both vegetated (by trees) and unvegetated flats undergoing extensive colonisation by plants and cut by the Cree estuary which had started to incise its course.

Lower Cree Estuary Area

The nature of the pre-Holocene/Holocene transition in the Creetown and Carsluith areas has already been discussed within the main text of this thesis. It is worth noting, however, that a transgressive lag of sand is evident at this boundary, possibly having been derived from re-working of the underlying fluvio-glacial deposits.

A disadvantage encountered during study of the Creetown and Carsluith areas was that the lower and upper tidal-flat sediments were not directly observed; their characteristics were only recorded in borehole logs. It is assumed, however, that the features already discussed in relation to the Upper Cree estuary area were also in existence in the Lower Cree area, although, as stated above, the areal extent of sediments in the latter area was fragmented due to infilling of isolated hollows.

Certain elements of the Lower Cree estuary sequence in both the Creetown and Carsluith areas are typical of a regressive estuarine setting, with coastal infilling. The fining-upwards sequence in the Creetown area is capped by marsh deposits as a result of infilling of the embayment and seaward progradation. In the immediately-adjacent Cassencarie-Carsluith area the sequence is modified, showing evidence of a pause in the marine regression - with the development of beaches and shore-parallel bars and of a spit complex. The bars are comparable to Greensmith and Tucker's (1973) shell ridges, derived from offshore banks, to form inshore ridges, sheets and shell pockets. The only difference between the two situations is that in the Lower Cree estuary there is a high gravel component in the ridge structures, possibly explained by derivation of the sediment from an adjacent fluvio-glacial deposit. Kraft _et al_. (1971), proposing sedimentary sequence models for a 'beach against highlands', described a beach environment impinging on low-lying pre-Holocene highlands (the equivalent of which are fluvio-glacial kame terrace deposits of the Carsluith area), which provided a source of sands, gravels and muds to the system.

These authors also described a spit complex, the regressive vertical sequence occurring where a spit migrated over the shallow marine area, with the spit sands and gravels overlying estuarine (_cf_. carse clays of the Lower Cree estuary) and shallow marine sediments.

The estuary-fill complex of the Cree area developed over a period of _c_. 10,000 years. During this time, relative sea-level changes were reflected in the character of the deposits. Infilling and progradation were rapid. It is thought that several 'erosive' breaks in the sequence are present. The recognition of these breaks and their relationship to sea-level changes are problematical due to the dynamic nature of erosion and deposition in an estuarine setting; evidence is constantly destroyed by reworking. In relation to the Severn estuary, Allen (1987b) gave details of several short-term coastal oscillations attributed to changes in the character and strength of waves at the shore. These were thought to be governed by weather changes or by shifting offshore shoals or by the morphology of the shore itself. Allen demonstrated that substantial advance and retreat of the shoreline can occur under stable sea-level conditions (stillstand) (cf. Jardine 1975, p. 184, in relation to the Solway Firth). The breaks or stillstands are characterised by emergence features such as palaeosols, roots, mud-cracks (Allen 1987a) and late stage drainage features which are recognisable in the geological record.

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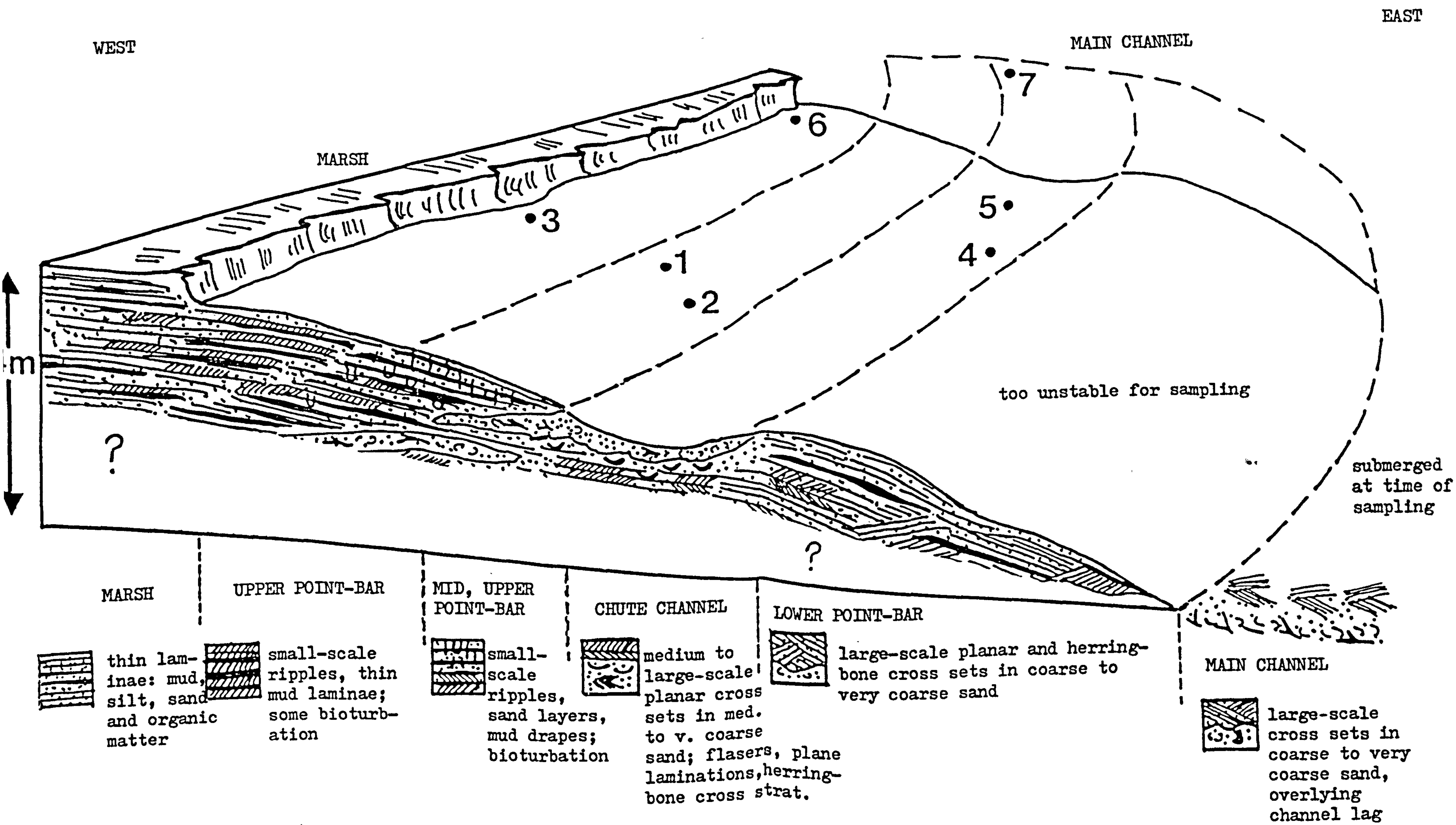


Figure 1. Facies/Environment Model for a modern point-bar during regressive marine conditions: A Case Study, Carsenestock Point-Bar, River Cree. Section West to East to show major sedimentary structures/facies (see also Figs. 10.14 and 10.15, pages 250 and 251 respectively). Box cores are numbered.

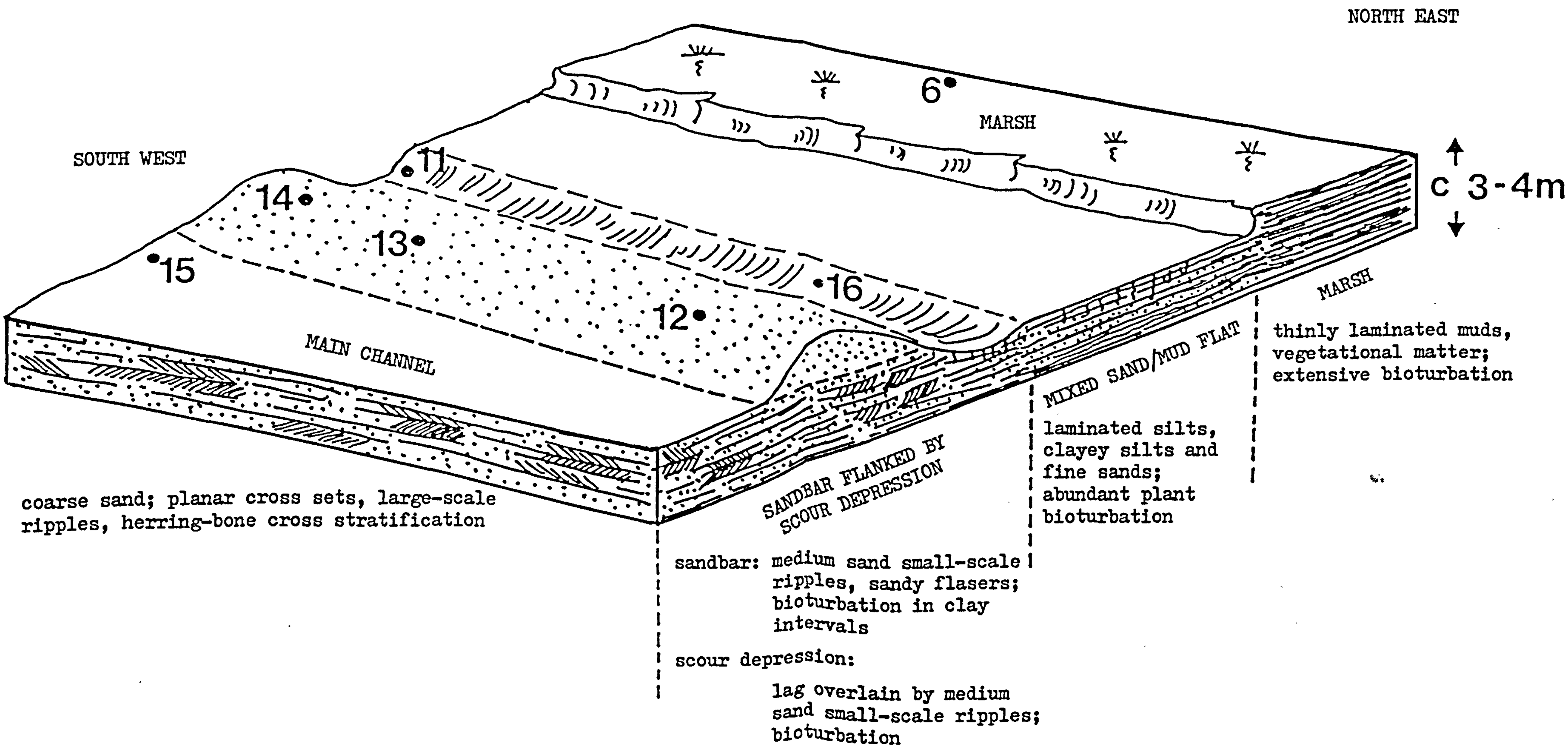
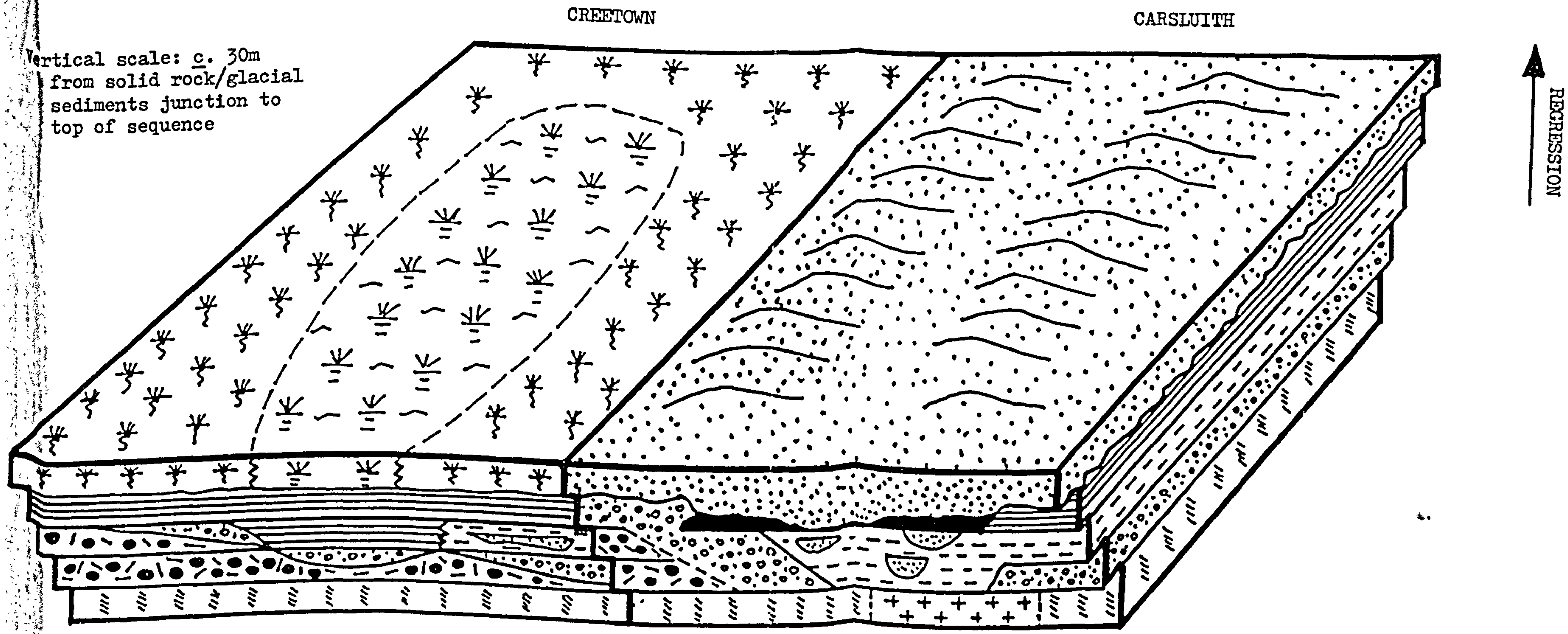


Figure 2. Facies/Environment Model for a modern tidal-flat during regressive marine conditions: A Case Study, Moneypool Burn. Section NE to SW to show major sedimentary structures/ facies (see also Figs. 10.22 and 10.23, pages 274 and 275 respectively). Box cores are numbered.



KEY

FACIES

Marsh infill (Creetown)
Beach sand cover (Carsluith)

Upper tidal-flats (peaty in places)

Lower tidal-flats, with channel sands

Fluvio-glacial sands and gravels

Glacial till

Granite/sandstones + siltstones (metamorphosed at Carsluith)

SUMMARY OF SEDIMENTARY STRUCTURES AND BIOLOGICAL FEATURES

Marsh: mottling of clays, abundant rootlets and peat traces
Beach: beach ridges, storm shell layers, beach laminations

Thinly bedded clays, lenticular sand units, some shells, occasional bioturbation, mottling towards tops of units, peat traces

Transgressive lag deposits, channel sand sheets and gravels interbedded with horizontal thinly-laminated clays, shell beds

Poorly developed stratification

Structureless

Figure 3. Block diagram to illustrate expansion of the sedimentary sequence and changing facies due to infilling of the Cree estuary during the Holocene marine regression. Case Study: Creetown and Carsluith areas.